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ABSTRACT

This technical specialty course is one of thirty-five courses designed for use by two-year postsecondary institutions in five nuclear technician curriculum areas: (1) radiation protection technician, (2) nuclear instrumentation and control technician, (3) nuclear materials processing technician, (4) nuclear quality-assurance/quality-control technician, and (5) nuclear reactor (plant) operator trainee. This course, Metrology, contains eight modules: Fundamentals of Metrology; Fixed Gages, Dividers, Calipers, and Micrometers; Gage Blocks, Mechanical Comparators, and Electronic Comparators; Angle Measurement Instruments, Optical Projectors, and Surface Texture Gages; Tolerancing; Calibrations; Statistics Techniques in Metrology; and The Total Measurement System. Each module follows a typical format including the following sections: introduction, module prerequisites, objectives, subject matter, exercises, materials, procedures, data tables, reference materials, and tests. (A master index and suggested program planning guides are also available--see CE 026 856 and CE 026 639-643.) (LRA)

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Nuclear Technology Series

COURSE 27

METROLOGY

CENTER FOR OCCUPATIONAL RESEARCH
AND DEVELOPMENT, INC.
4800 LAKEWOOD DRIVE
WACO, TEXAS 76710

JUN 1980

U.S. DEPARTMENT OF HEALTH,
EDUCATION & WELFARE
NATIONAL INSTITUTE OF
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PREFACE

ABOUT NUCLEAR TECHNOLOGY MODULES

The modules - developed by TERC-SW for use in two-year postsecondary technical institutions to prepare technicians for employment - are useful in industry for updating employees in company-sponsored training, and as laboratory texts in engineering schools. The principles, techniques and skills taught in the modules, based on tasks that nuclear technicians perform, were obtained from a nationwide advisory committee of employers of nuclear technicians. Each module was written by a working technical expert/experienced writer team and tested with students.

A module contains the following elements:

Introduction, which identifies the topic and often includes a rationale for studying the material.

Module Prerequisites, which identify the material a student should be familiar with before studying the module.

Objectives, which clearly identify what the student is expected to know for satisfactory module completion. The objectives, stated in terms of action-oriented behaviors, include such action words as operate, measure, calculate, identify and define, rather than words with many interpretations, such as know, understand, learn and appreciate.

Subject Matter, which presents the background theory and techniques supportive to the objectives of the module. Subject matter is written with the technical student in mind.

Exercises, which provide practical problems to which the student can apply this new knowledge.

Materials, which identify the equipment required to complete the laboratory procedure.

Procedures, which is the experiment section, or "hands-on" portion of the module (including step-by-step instruction) designed to reinforce student learning.

Data Tables, which are included in most modules for the first year (or basic) courses to help the student learn how to collect and organize data.

Reference Materials, which are included as suggestions for supplementary reading/viewing for the student.

Test, which measures the student's achievement of the prestated objectives.

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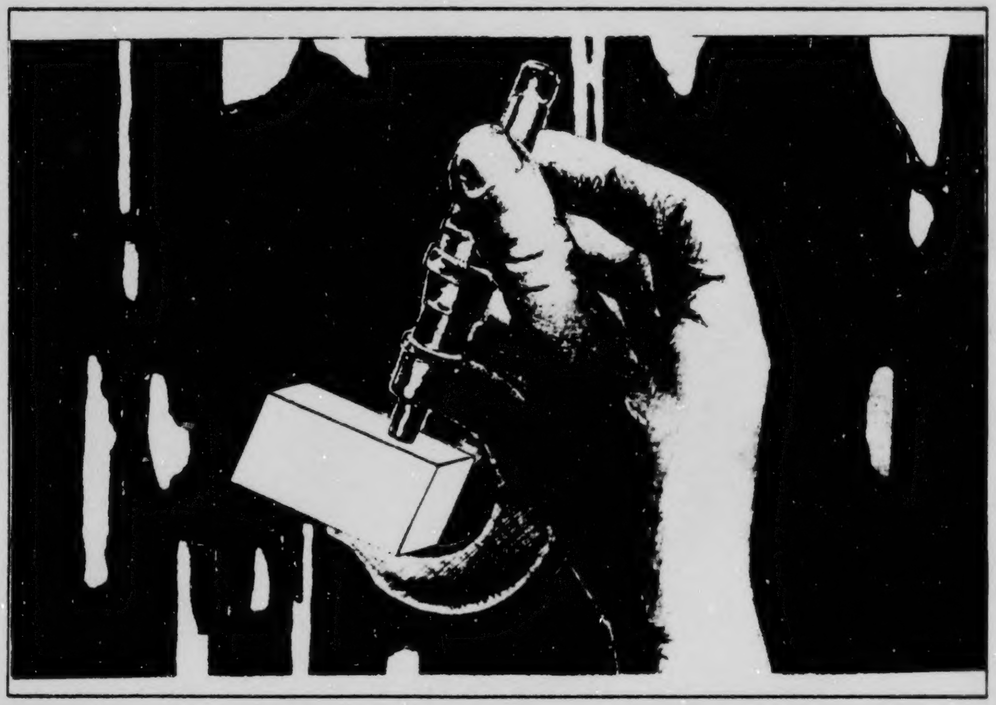
Module 27-6 Calibration
Module 27-7 Statistics Techniques in Metrology
Module 27-8 The Total Measurement System

NUCLEAR TECHNOLOGY

MODULE 27 - 1

FUNDAMENTALS OF METROLOGY



COURSE 27: METROLOGY

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 27 METROLOGY

⇨ MODULE 27-1	Fundamentals of Metrology
MODULE 27-2	Fixed Gages, Dividers, Calipers and Micrometers
MODULE 27-3	Gage Blocks, Mechanical Comparators and Electronic Comparators
MODULE 27-4	Angle Measurement Instruments, Optical Projectors and Surface Texture Gages
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MODULE 27-6	Calibration
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INTRODUCTION

Metrology is a science of measurement that is concerned with accurate and reliable measurements. While metrology deals with all units of measurement, this course pertains to dimensional inspection.

Some thought provoking questions can quickly be brought to mind when considering dimensional inspections. Considering a wood or steel ruler that is scribed in inches and is twelve inches long, a number of questions can be asked. What is the basis for the length that is termed one foot or one inch? Of the millions of twelve inch rulers in existence, is each exactly one foot? Is the scale of each uniformly scribed? Will each give the same measurement results? Are there any environmental effects on the measurement results? Is a scale of 1/32 inch increments more readable than a scale of 1/64 inch increments? Should fractions or decimals be used to indicate portions of an inch? When should a device more accurate than the ruler be selected for the measuring instrument?

This module describes the fundamental concepts on which answers to these types of questions are based. This module presents basic theory of measurements. Later modules of this course describe the application of these concepts to specific measurement devices and procedures.

The Nuclear QA/QC Technician has an important role with respect to metrology. This role is in relation to the dimensional inspector who makes measurements and the calibration technician who sets the accuracy of measuring devices. This course as a whole is designed to equip the student/trainee to perform the following tasks of the Nuclear QA/QC Technician:

- Prepare inspection procedures that describe the measuring device, specific techniques, and records to be used.

- Prepare sampling inspection plans.
- Investigate and report the sources of error in measurements and actions to reduce error.
- Monitor or audit inspection functions.
- Monitor or audit calibration functions.

MODULE PREREQUISITES

None.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. State two reasons that metrology must be applied to the design, construction and operation of nuclear power plants.
2. Define the following terms:
   a. Standard
   b. Accuracy
   c. Precision
   d. Readability
   e. Sensitivity
   f. Linearity
   g. Measurement
   h. Tolerance
3. Describe the role of standards in a measurement process.
4. Describe the hierarchy of standards.
5. State the purpose of the sensors, transducers, and

readout.

6. List the two principles that govern the accuracy of a measurement.
7. Name four factors that affect precision of a measurement process.
8. Discuss the use of a tolerance-to-readability ratio.
9. Name the factors that affect the sensitivity of a measuring device.
10. Name the factors that affect the readability of a measuring device.
11. Distinguish between systematic error and random error.
12. Name six sources of errors that affect accuracy and describe contributing factors.
13. Demonstrate ability to detect errors in a linear measurement with a rule or scale.

SUBJECT MATTER

FUNDAMENTALS OF METROLOGY

Need for Metrology

Dimensional metrology had its origins when humans began to develop products, goods and services to meet life's needs. It was soon recognized that established rules must be set in order to ensure fit and function of products. That is to say, some type of dimensional control would have to be established to allow component parts to fit correctly during assembly and function properly when installed and subsequently tested. In addition to the concept of fit and function was the basic idea of interchangeability of parts and components. It became clear that standards needed to be established to ensure proper duplication of components.

The need for ensuring fit, function, and interchangeability is apparent when envisioning the complexities of a nuclear power plant. The nuclear power plant is comprised of some 80 to 100 major systems and represents an investment in 1978 of about $1,000,000,000. Each major system consists of subsystems and components. Certain components can cost a few million dollars each. Thousands of vendors are involved with the manufacture and installation of these components, subsystems, and systems. With all of the complexities, the end result must be the integrated operation of all systems, such that power is safely produced and transmitted to consumers. This task would be impossible without metrology. For example, a relatively simple component such as a valve, involves numerous vendors and complexities. As shown in Figure 27-1-1, a valve manufacturer who performs practically all processing and assembly of parts of a valve still relies on several other vendors for raw materials and certain parts. Frequently, some of the processing steps shown for the valve manufacturer are subcontracted to additional vendors. Dimensional control is absolutely necessary if all the parts are to fit at assembly and function properly at test and after installation.

The valve shown in Figure 27-1-1 is a type that is bolted to flanged pipe when installed. It is not difficult to imagine the consequences of an out of alignment condition of the bolt holes in the valve body and the pipe flanges. Since redrilling the bolt holes would probably not leave sufficient material between the holes, either new flanges or a new valve body would be needed. This type of concern for fit-up at installation is compounded by the more complex components, such as a reactor pressure vessel. The reactor pressure vessel has external interfaces with support mounts, reactor coolant piping, a closure head, and other piping systems. Misorientation of any of these interfaces can result in hundreds of thousands of dollars in repair costs.

These few illustrations of interfacing dimensions and the concept of interchangeability show that metrology is absolutely necessary to protect the investment by each vendor supplying hardware and by the ultimate owner, the nuclear utility.

UNITS OF MEASUREMENT

Units

What is a unit? People use units throughout their lives without necessarily realizing it. For example, if a person wished to meet a friend at a certain place and a given time, it would be confusing if units were not used in the conversation. For example, one might say "I will see you in 2 ___ at the restaurant which is 25 ___ up the road." Although one may guess what the units might be, there would still be some doubt. For example, is the meeting to be

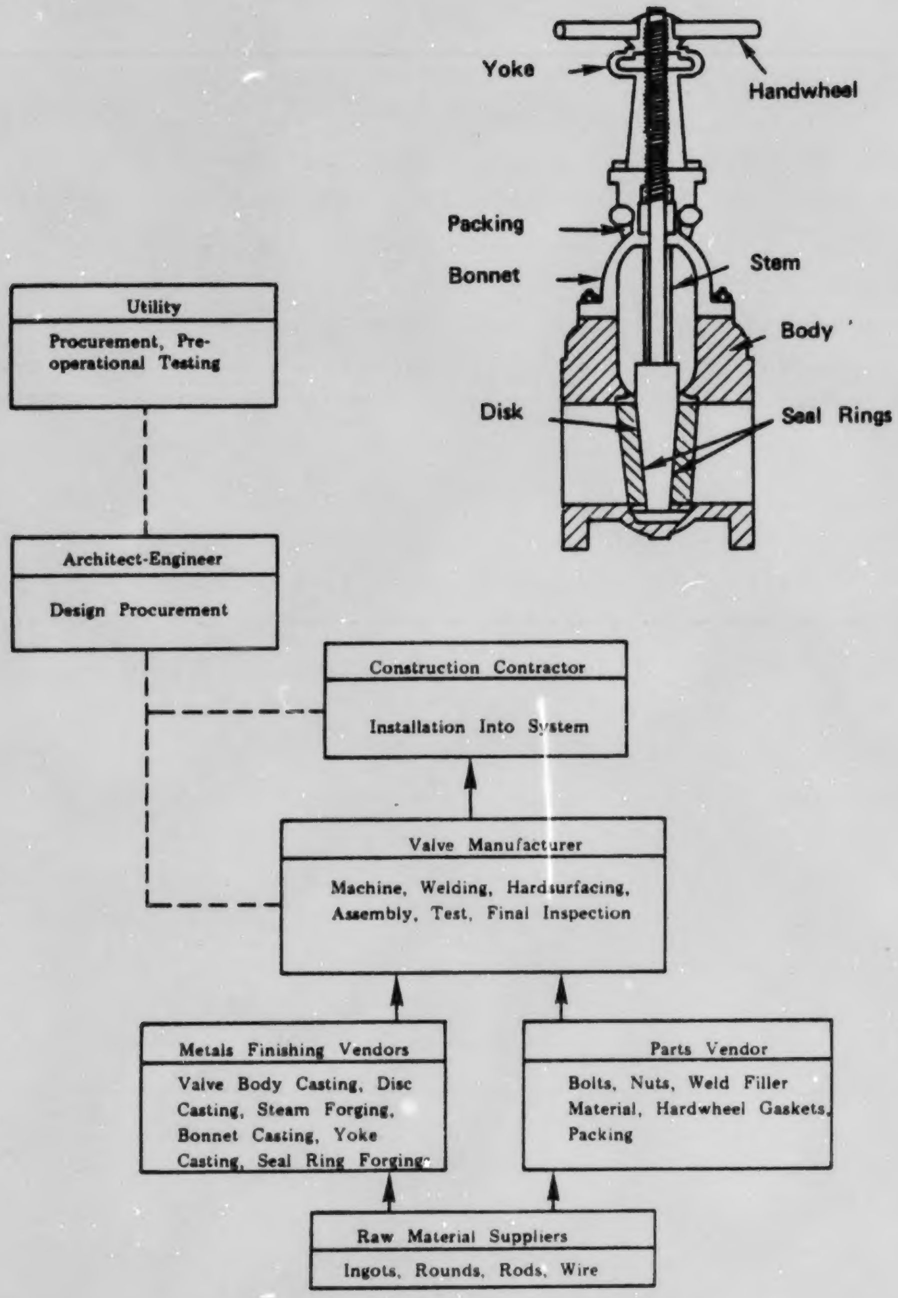

Yoke
Handwheel
Packing
Bonnet
Stem
Body
Disk
Seal Rings
Utility
Procurement, Pre-operational Testing
Architect-Engineer
Design Procurement
Construction Contractor
Installation Into System
Valve Manufacturer
Machine, Welding, Hardsurfacing, Assembly, Test, Final Inspection
Metals Finishing Vendors
Valve Body Casting, Disc Casting, Steam Forging, Bonnet Casting, Yoke Casting, Seal Ring Forging
Parts Vendor
Bolts, Nuts, Weld Filler Material, Hardwheel Gaskets, Packing
Raw Material Suppliers
Ingots, Rounds, Rods, Wire

Figure 27-1-1. Vendor Interfaces

held in 2 minutes or 2 hours? Is the restaurant 25 feet or 25 miles up the road? These clarifying terms are called units.

Definition of a Unit

A unit is a determined quantity that has been adopted as a standard of measurement. It is used to inform us of how much of a quantity we are working with. Examples of units are feet, inches, centimeters, pounds, kilograms, gallons, grams and seconds. In general, a unit is fixed by definition and is independent of physical conditions such as temperature and pressure.

Development of Some Customary Units

It is not the intent of this module to describe the development of units. However, a brief discussion on development of units of length should assist the student/trainee to appreciate the need for standardization of units of measurement.

The cubit was the first recorded unit used by ancient people to measure length. There were several cubits of different magnitudes that were used. The common cubit was the length of the forearm from the elbow to the tip of the middle finger. It was divided into the span of the hand (one-half cubit), the palm or width of the hand (one-sixth), and the digit or width of a finger (one twenty-fourth). The Royal or Sacred Cubit, which was 7 palms or 28 digits long, was used in constructing buildings and monuments and in surveying. The inch, foot, and yard evolved from these units through a complicated transformation not yet fully understood. Some believe they evolved from cubic measures; others believe they were simple proportions or multiples of the cubit. In any case, the foot was inherited from the Egyptians by the Greeks and

Romans. The Roman foot was divided into both 12 unciae (inches) and 16 digits. The Romans also introduced the mile of 1,000 paces or double steps, the pace being equal to 5 Roman feet. The Roman mile of 5,000 feet was introduced into England during the occupation. Queen Elizabeth, who reigned from 1558 to 1603, changed by statute the mile to 5,280 feet or 8 furlongs, a furlong being 40 rods of 5½ yards each.

The introduction of the use of the yard as a unit of length came later, but its origin is not definitely known. Some believe the origin is the double cubit, others believe that it originated from cubic measure. Regardless of its origin, the early yard was divided by the binary system into 2,4,8 and 16 parts called the half-yard, span, finger, and nail. The association of the yard with the "gird" or circumference of a person's waist or with the distance from the tip of the nose to the end of the thumb of Henry I are probably standardizing actions, since several yards were in use in Great Britain.

The need for a single worldwide coordinated measurement system was recognized over 300 years ago. After several attempts by various persons in the sixteen hundreds, the French Academy of Sciences appointed a Commission in 1790 to "deduce an invariable standard for all the measures and all the weights". The Commission developed what has become known as the Metric System of Weights and Measures. The basic unit of length was the meter which was defined as one tenmillionth of the distance from the north pole to the equator along the meridian of the earth running near Dunkirk, France and Barcelona, Spain.

Subsequently, the International Bureau of Weights and Measures located at Sevres, France assigned to its General Conference the responsibility of refining the Metric System. In 1960, the General Conference adopted an extensive revision and simplification of the Metric System. The new system was termed "International System of Units" which is abbreviated SI for the French "System International". The unit of length remained as the meter, but the definition of meter was based on a number of wavelengths of light emitted by Krypton-86 in a vacuum. Today, the United States National Bureau of Standards bases its definitions of weights and measures on the definitions of the SI System. These SI definitions are given in Table 27-1-1. This table lists the reference standards upon which the basic SI Units are based. It must be emphasized that these are reference standards which allow us to accurately define each of these basic units. These are not to be confused with how the parameters of length, mass, time, etc. are actually measured on the job.

U. S. National Bureau of Standards

The United States National Bureau of Standards was established by an act of Congress in 1901 to serve as a national scientific laboratory in the physical sciences and to provide fundamental measurement standards for science and industry. The United States developed, from the British System of Weights and Measures, a system of weights and measures that contains both equalities and inequalities with the British System. In both systems, length measurements are identical, e.g., 12 inches = 1 foot, 3 feet = 1 yard, and 1760 yards = 1 international mile. But differences exist with respect to other measures such as dry volume (bushel) and liquid volume (gallon). The U.S. National Bureau of Standards establishes the definition of units within the U.S. System of Weights and Measures and maintains conversion factors to convert any of the U.S. units to their corresponding British and SI units.

TABLE 27-1-1 Definitions of Fundamental Units of the SI System

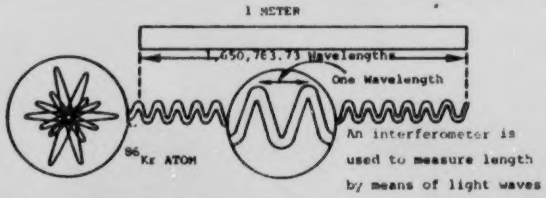
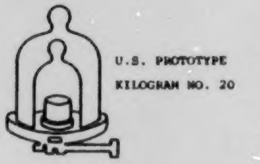
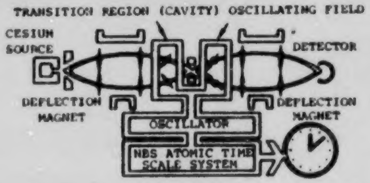
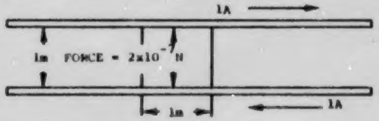
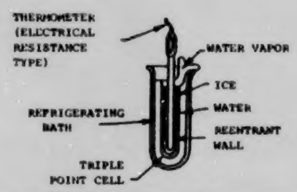
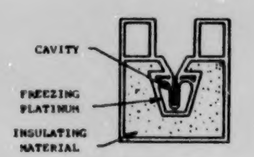
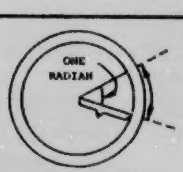
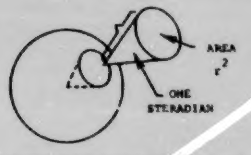
Meter	The meter is defined as 1,650,763.73 wavelengths in vacuum of the orange-red line of the spectrum of krypton-86.	 1 METER 1,650,763.73 Wavelengths One Wavelength ^{86}Kr ATOM An interferometer is used to measure length by means of light waves
Kilogram	The standard for the unit of mass*, the kilogram, is a cylinder of platinum-iridium alloy kept by the International Bureau of Weights and Measures at Paris. A duplicate in the custody of the National Bureau of Standards serves as the mass standard for the United States. This is the only base unit still defined by an artifact. * Weight is a commonly used term for mass.	 U.S. PROTOTYPE KILOGRAM NO. 20
Second	The second is defined as the duration of 9,192,631,770 cycles of the radiation associated with a specified transition of the cesium-133 atom. It is realized by tuning an oscillator to the resonance frequency of cesium-133 atoms as they pass through a system of magnets and a resonant cavity into a detector.	 TRANSITION REGION (CAVITY) OSCILLATING FIELD CESIUM SOURCE DETECTOR DEFLECTION MAGNET DEFLECTION MAGNET OSCILLATOR NBS ATOMIC TIME SCALE SYSTEM
Ampere	The ampere is defined as that current which, if maintained in each of two long parallel wires separated by one meter in free space, would produce a force between the two wires (due to their magnetic fields) of 2×10^{-7} newton for each meter of length.	 1A 1m FORCE = 2x10^{-7}N 1m 1A

TABLE 27-1-1 Definitions of Fundamental Units of the SI System (continued)

Degree Kelvin	The kelvin is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. The temperature 0 K is called "absolute zero".	The standard temperature at the triple point of water is provided by a special cell, an evacuated glass cylinder containing pure water. When the cell is cooled until a mantle of ice forms around the retentrant well, the temperature at the interface of solid, liquid, and vapor is 273.16 K. Thermometers to be calibrated are placed in the reentrant well.  THERMOMETER (ELECTRICAL RESISTANCE TYPE) WATER VAPOR ICE WATER REFRIGERATING BATH REENTRANT WALL TRIPLE POINT CELL
Candela (lumens)	The candela is defined as the luminous intensity of 1/600,000 of a square meter of a blackbody at the temperature of freezing platinum (2045 K).	The SI unit of light flux is the lumen (lm). A source having an intensity of 1 candela in all directions radiates a light flux of 4 π lumens.  CAVITY FREEZING PLATINUM INSULATING MATERIAL
Radian (plane angle)	The radian is the plane angle with its vertex at the center of a circle that is subtended by an arc equal in length to the radius	
Steradian (solid angle)	The steradian is the solid angle with its vertex at the center of a sphere that is subtended by an area of the spherical surface equal to that of a square with sides equal in length to the radius.	 AREA r^2 ONE STERADIAN

This course will use the U.S. System of Weights and Measures. Of most interest are the units of length, area, and plane angles. Conversion factors for these units to the SI System are given in Table 27-1-2.

It is noted that the U.S., England, and Canada reached agreement in 1960 on the standardized conversion of 1 inch equalling exactly 2.54 centimeters. Prior to 1960, differences existed among the three countries on this conversion. Some literature is still in use which reflects such differences. The QA/QC technician must ensure that the most current definitions of units and conversion factors are being used. Periodic publications by the U.S. National Bureau of Standards identify the current definitions of units and conversion factors.

Units of Length International Measure *

Units		Inches	Feet	Yards	Centimeters	Meters
1 inch	=	1	0.083 333 33	0.027 777 78	2.54	0.025 4
1 foot	=	12	1	0.333 333 3	30.48	0.304 8
1 yard	=	36	3	1	91.44	0.914 4
1 centimeter	=	0.393 700 8	0.032 808 40	0.010 936 13	1	0.01
1 meter	=	39.370 08	3.280 840	1.093 613	100	1

Units	Square Inches	Square Feet	Square Yards	Sq. Centimeters	Square Meters
1 sq. inch	1	0.006 944 444	0.000 771 604 9	6.451 6	0.000 645 16
1 sq. foot	144	1	0.111 111 1	929.030 4	0.092 903 04
1 sq. yard	1296	9	1	3361.273 6	0.836 127 36
1 sq. cm	0.155 000 3	0.001 076 391	0.000 119 599 0	1	0.000 1
1 sq. meter	1550.003	10.763 91	1.195 990	10 000	1

Units of Plane Angles

1 radian = 57.296 degrees

1 degree = 0.01745 radian

NOTE: Underlined values are exact; others are approximate.

Table 27-1-2. Conversion Factors

STANDARDS

Definitions

There are two types of standards considered in dimensional metrology. One type of standard is the unit of reference by which a given parameter is measured. For example in the SI system, length is measured in meters, mass in kilograms and time in seconds. Table 27-1-1 denotes the precise physical standard by which each of these is units is defined. The purpose of these standards is to provide a common reference by which all basic physical parameters, such as length, mass, time, etc., can be compared.

Another type of standard used in dimensional metrology is a rule or authority by which services are provided or a product is manufactured. This second definition of a standard pertains to the written criteria governing products, processes or services.

Hierarchy of Standards for Units

One does not compare all measurements with the corresponding standard given in Table 27-1-1. For example, it is totally impractical to compare all length measurements with the orange-red wavelengths of Krypton-86. It is much more practical for each organization involved in measurements to possess or have ready access to other suitable standards. Accordingly, a hierarchy of standards has evolved as shown in Figure 27-1-2.

Referring to Figure 27-1-2, four divisions of standards are shown. The primary reference standards are those maintained by the U.S. National Bureau of Standards. These standards consist of a duplicate copy of the International Kilogram plus measuring systems that are responsive to the definitions of units given in Table 27-1-1. These standards serve as the common reference for measurements within the

United States for both the SI and U.S. System of Weights and Measures, and, hence, are the primary reference standards.

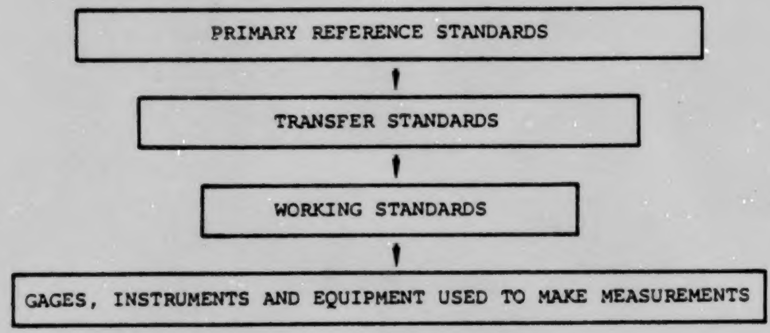

PRIMARY REFERENCE STANDARDS
TRANSFER STANDARDS
WORKING STANDARDS
GAGES, INSTRUMENTS AND EQUIPMENT USED TO MAKE MEASUREMENTS

Figure 27-1-2. Hierarchy of Standards

The transfer standards indicated in Figure 27-1-2 are those maintained by industry for the sole purpose of "transferring" accuracy of measurement to the next lower level of standards in the hierarchy. Transfer standards are compared by the National Bureau of Standards with the defined unit of measure. Such a "calibrated" transfer standard may then be used to determine accuracy of other transfer standards of the same fundamental unit of measurement. Economics governs the number of transfer standards in existence. It should be stressed that transfer standards are ordinarily used for calibration and not for actually making measurements of product.

The working standards indicated in Figure 27-1-2 are those possessed by or readily available to every organization that makes measurements of product. The working standards are compared to the transfer standard to determine their accuracy. Working standards can be used to making measurements if a high degree of accuracy is required.

The measuring devices indicated in Figure 27-1-2 are used to make measurements. The accuracy of these devices is known by their comparison with the working standard. Thus, the total hierarchy offers the provision for determining the ability of a measuring device to make a measurement in units embodied by the primary reference standard (e.g., national standard). The hierarchy permits billions of measuring devices to be compared economically with the national standard.

Standards by Adoption

Written standards in use in the United States are developed by either government agencies, professional societies, or associations representing using industries. Those developed by professional societies and user associations are frequently adopted by the National Standards Institute as a national standard. These standards may also be made mandatory for use by governmental statute or regulation. In any event, when two or more using parties agree to comply with written criteria, a standard has been adopted.

Some examples of written standards pertaining to metrology are as follows:

- Military Standard 105D, Sampling Procedures and Tables for Inspection by Attributes - This standard defines criteria and procedures for use of statistical sampling techniques.
- Department of Commerce Handbook H-28, Screw Thread Standards for Federal Services - This standard defines classes of threaded fasteners and their precision.
- Department of Commerce GGG-G-15, Gage Blocks and their Accessories - This standard defines classes of gage blocks and their accuracies.
- American National Standards Institute Y-14.5, Dimensioning, and Tolerancing - This standard defines

methods of designating form features on drawings and the interpretation of such designations.

FUNDAMENTAL CONCEPTS OF MEASUREMENTS

Concepts

Fundamental concepts and terms are used within any discipline. In metrology the primary concepts are: standards, accuracy, and precision. The secondary concepts are: readability, sensitivity, and linearity. Standards were previously introduced. Prior to introducing the other five terms, the term "measurement" will be defined and illustrated and the fundamental design of measuring devices will be reviewed.

Definition of Measurement

Measurement is the act or process of ascertaining the dimensions (or other features) of something by comparing its dimensions (or other features) to an accepted standard utilizing devices designed for that type of measurement. This means that, in order for measurement to occur, the measuring device used to gage the feature must be compared to a standard. In this manner, the measurement result has validity because the accuracy of the measuring device has been determined.

Fundamental Design of Measuring Devices

All measuring instruments or devices have common design features: sensor, transducer, and readout. Depending on the specific measuring device, the same part may serve in multiple capacities or individual parts may exist for each of these three components.

- Sensors - Sensors are the elements of instruments that detect the units to be measured. The contacts of a micrometer are considered as the sensor in that the spacing of the contacts detects the length units being measured. Tracers of surface roughness measuring equipment are sensors of surface topography in that these tracers follow the surface contour. The sensory state of a measuring system should ensure the desired change of readout per unit of measured quantity and should also be sensitive to all required characteristics of the measured quantity.

- Transducers - The transducer is a device that responds to a given parameter to be measured by producing a signal which is related to one or more variables of that parameter. Such devices vary from the delicate and reliable transducers of space vehicle telemetry systems to the simple air gages for measuring cylinder bores.
- Readout - Readout is the indication of the measured feature in the desired units. Readout may be by direct indicating, digital or recording.

Figure 27-1-3 shows the sensor, tranducer, and readout of a measuring device. Note the following features of this measuring device.

- the anvil is the sensor
- the internal lead screw functions as the transducer
- the thimble functions as the readout.

Accuracy

Accuracy is defined as the agreement of a measurement with the true value of the measurement quantity. Accuracy is the agreement of the recorded value with the value that would have been obtained had the dimension been directly compared to the primary reference standard. Recall that the primary reference standard was the most accurate technique

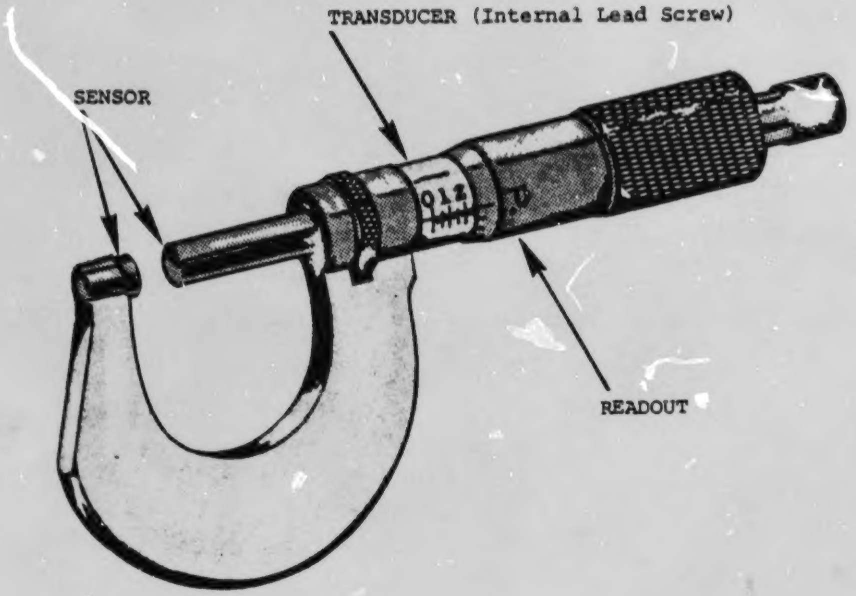


Figure 27-1-3. Illustration of Basic Design

for measurement of a given parameter. Therefore, in dimensional metrology, one is attempting to reference the accuracy of a given measurement back to this primary standard or "most accurate" measurement.

Considering only the accuracy of the measuring device and intermediate standards, the accuracy could be determined if the accuracy of each intermediate Standard were known. However, this would not account for human accuracy in using and reading the measuring device nor other factors such as temperature effects. Sources of error affecting accuracy are described later in this module. Module 27-8 describes the total measurement system as a composite of the first seven modules and, thereby, describes the predominant factors affecting accuracy.

Accuracy of measurement is essential to the ability to ensure fit, function and interchangeability. Two principles for achieving accuracy are:

- The more alike two things are, the more accurately they can be compared.
- The operations performed on the standard and the unknown must be as identical as feasible.

The first principle involving the accuracy of measurements could be demonstrated by comparing a meterstick to a yardstick of the same accuracy. Measurements involving these two devices require the use of conversion factors which introduce another source of error. It would be easier to compare one meterstick to another meterstick or a yardstick to another yardstick.

The second principle involving the accuracy of measurement advises that to achieve greater accuracy in a measurement, the same technique and the same environment should be employed when comparing a standard and an unknown.

Precision

Precision is the repeatability of the measuring process. One of the suggested activities listed for this module is that the width of a vee block be measured ten times with wood rule and then again with a steel rule. Completion of this basic measurement exercise will probably result in the recording of different values for the measured dimension. While accuracy of the measurement contributed to the results in that case, if the same individual uses the same measuring device to repeatedly measure the same dimension, a scatter of results is likely. Precision determines how closely identical values are obtained when repeating the same measurement at various intervals, or duplicating them by different instruments.

Inherent features of the measuring device and the measurement technique and materials are the main factors affecting precision. Each measuring device has its own precision. The precision of the measurement technique (procedure) is affected by human factors, the use of different devices or materials, and environmental changes.

It should be noted that the concepts associated with standard, accuracy, and precision represent the heart of a measurement system. Measurements are unreliable if each of the three cannot be quantified for the corresponding measurement procedure. The discussion of error later in this module and the remaining modules of this course will describe standards, accuracy, and precision with respect to the types of measuring devices presented.

Secondary Concepts

The secondary concepts are just as important as the principal concepts. However, these concepts are more directly related to the measuring instruments' ability to measure to a standard with accuracy and precision. These secondary concepts are readability, sensitivity and linearity.

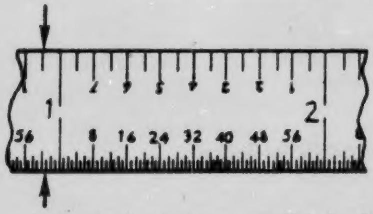
Readability

Readability is the susceptibility of a measuring device to having its indications (readout) converted to a meaningful number. For example, a worn out ruler whose graduations are difficult to read could not be used effectively in making an accurate measurement. Similarly a ruler which is graduated in one-eights of an inch may be difficult to use when trying to read to the nearest one-tenth of an inch. Likewise, attempts to graduate a ruler in extremely fine increments, e.g., 0.010" or less, makes the ruler unreadable. The term readability is sometimes used interchangeably with discrimination. However, discrimination means the increments of the least significant unit on a measuring device. One example is a scale graduated to the nearest one-tenth of an inch. This scale could not be used to make measurements to the nearest one-hundredth of an inch because it would not have sufficient discrimination. Readability refers to the ability of the user to read to the smallest unit on the measuring device using specified inspection procedures. Line-graduated measuring devices that have very fine discrimination may not be very readable.

Factors affecting readability of a measuring device are:

- the skill of the user
- the clarity of the readout on the instrument
- the type of readout, e.g., scale, numeric display, digital
- the level of lighting.

Finest division: 1/16 inch
Discrimination: 1/16 inch



Finest division: 1/64 inch
Discrimination: 1/64 inch

Figure 27-1-4. Readability and Discrimination

The lower scale in Figure 27-1-4 discriminates to 1/64 of an inch while the upper scale can only reliably discriminate to 1/16 of an inch. The readability of the upper scale is greater than that of the lower scale, i.e., it is easier to see the divisions.

Readability affects the selection of the measuring device to be used. Tolerance of the dimension to be measured governs such selection. (Tolerance is defined as the range or limit of measurement values that are acceptable to the specified standard.) For example, if the tolerance of the feature of a part is plus or minus 0.125 inch, an ordinary scale or steel rule is suitable. If that same feature has a tolerance of plus or minus 0.005 inch, a vernier with a readout in increments of 0.001 inch should be considered.

Tolerance-to-Readability Ratio

Tolerance-to-readability ratio determines the selection of a measuring device for a specific application. There are two rules with respect to tolerance-to-readability ratio. One is to select instruments having at least a 10 to 1 ratio and the other is to select instruments having at least a 4 to 1 ratio. While the 10 to 1 rule is more conservative, it frequently becomes impractical when calibrating instruments. When the 10 to 1 rule is applied to the hierarchy of standards in the calibration process, the "state-of-the art" of inspection capability is often exceeded. Hence, the 4 to 1 rule is more practicable. For fixed limit tolerances, readability becomes a factor as the limit is approached. Examples of both rules for selection of measuring devices are given in Table 27-1-3.

Sensitivity

Sensitivity is the ability of a measuring device to detect differences in a quantity being measured. For example, if the device will detect differences of 0.0002 inch in measured values, its sensitivity is 0.0002 inch. Typical sensitivities of commonly used measuring devices are given in Table 27-1-4.

Table 27-1-3. Examples of 10/1 and 4/1 for Selection of Instruments

Size	Tolerance	Minimum Readability of Instrument	
		10 to 1 Rule	4 to 1 Rule
6.50 ± .05	0.10	0.01	0.025
3.250 ± 0.001	0.002	0.0002	0.0005
5.5000 ± 0.0001	0.0002	0.00002	0.00005
8.750 Maximum	Maximum Limit	0.01 Below 8.740 0.001 Between 8.740 and 8.749 0.0001 Between 8.749 and 8.750	0.025 Below 8.740 0.0025 Between 8.740 and 8.749 0.00025 Between 8.749 and 8.750

Table 27-1-4. Measuring Sensitivities in General

TYPE OF MEASURING DEVICE	TYPICAL SENSITIVITY	TYPE OF MEASURING DEVICE	TYPICAL SENSITIVITY
Line Graduated Rules and Tapes	1/32 or 1/64 inch	Vernier Caliper	0.0001 inch
Micrometer Without Vernier	0.001 inch	Micrometer with Vernier	0.0001 inch
Bevel Protractor Without Vernier	1 Degree	Bevel Protractor with Vernier	5 Minutes
Mechanical (Dial) Indicators	From 0.00005 to 0.0001 inch	Electronic Comparators	From 0.000 001 to 0.0001 inch

Factors affecting sensitivity include:

- the ability to dampen an instrument. (Dampening refers to a process of reducing an instruments' tendency to "hunt" for the measurement value. This can be a particular problem with instruments using an electronic readout.)
- the degree of drift of electronic or pneumatic gages.
- the skill of the user.
- the overall precision of the measuring device.
- environmental effects. Sensitivity may be affected by ambient temperature, humidity, and corrosiveness of the environment.

Selection of the measuring device to be used with respect to sensitivity is based on tolerance and environmental conditions. The 4 to 1 rule applicable to readability applies to sensitivity. That is, if the measuring device has a sensitivity of 25% of the tolerance, it is a suitable device.

Linearity

Linearity is the agreement of the measurement throughout the full range of any given measuring device with the true incremental unit increases of the unit being measured. Linearity can be envisioned as the change in accuracy over the range of the measuring device. For example, Figure 27-1-5 shows an example of a linear scale and a non-linear scale.

Linearity involves the precise spatial relationship of markings of readout on the instrument and the ability of the instrument to proportionally transmit variations in value of the feature from the sensor to the readout. For example, the linearity of a clock is affected by the spatial relationship of the dial markings and the ability of the clock's mechanism to drive the hands through each

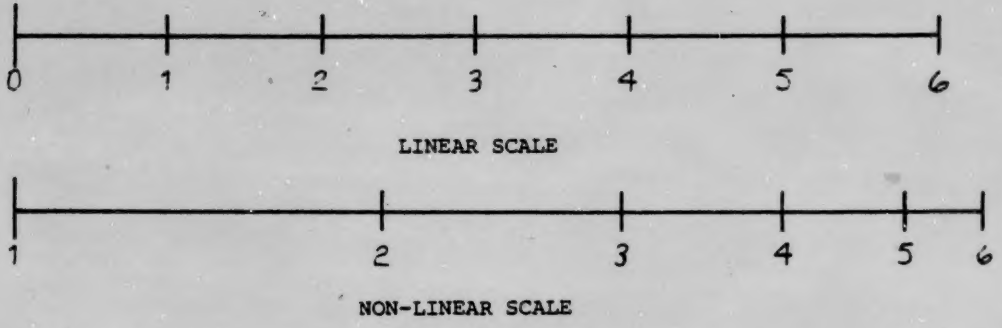


Figure 27-1-5. Examples of Linear and Non-Linear Scales

increment of marking in the same time period.

Linearity of an instrument is affected by:

- Manufacturing tolerances in making the instrument.
- Design of the instrument, for example, certain types of instruments contain features which are inherently non-linear and compensatory measures are included in the design.
- Wear or deterioration of the transmitting or amplifying device from sensor to readout.

Linearity of an instrument is best determined by comparison with standards representing increments of the range of the instrument. This feature of a measuring device is normally checked during "calibration", that is, when it is compared and adjusted to standards. Linearity becomes suspect when measurements by one instrument cannot be repeated with expected precision by another same or equivalent type of instrument.

ERROR OF MEASUREMENT

Error

The difference between the measured value and the true value is the error. Except for unusual cases, the inspector never knows an absolutely *true value.* One must always assume that there is some error in a given measurement. When a measurement is repeated the results will disagree by an amount called the *discrepancy*. The causes of discrepancy must also be the causes of differences between the readings and the true value.

Error can be positive or negative, that is, the measurement value may be either side of the true value. All measurements have some error. The objective of the metrology program is to provide sufficient accuracy to ensure fit, function, and interchangeability.

Types of Error

Errors are typically categorized as random or systematic. Random errors are primarily associated with the human element and result from inaccurate readings and calculation, improper use of instruments, and errors in recording values. Such errors are difficult to predict, but can be evaluated statistically from past results. The smaller the *random* errors, the greater the precision. Systematic errors are those which are generally controllable or measurable. They include the instrument's capabilities, environmental condition, and procedural techniques. In other words, if all of the individual readings are the same it does not mean that there are no errors. They could all vary from the true value by a uniform or *systematic error.* A good example is a kink in a steel tape. All measurements that include the kink will have the same amount of positive error. They will be too long. As the value of *systematic* errors decreases, accuracy increases. Experience shows that most measurements contain a combination of both random and systematic errors.

Sources of Error

Error of measurement is the composite effect of all sources of error. These sources of error may be subtle and require painstaking research to locate within the measurement procedure. However, each measurement procedure is susceptible to error from six sources. These sources are the measuring device, the operator, a group of operators, materials, procedure, and laboratory.

- Errors of the Measuring Device - Errors may exist in a specific measuring device or between like types of measuring devices. The errors are associated with nonlinearity, imprecision, instability or drift, and sensitivity to features other than that being measured. For example, temperature, electromagnetic fields, electrostatic fields, and vibration. Also, when use of the measuring device involves supplementary apparatus, sources of error include the precision of locating the apparatus, the tightness of mechanical joints and the conductance of electrical connections.
- Errors of an Individual Operator - A single individual obtains diverse results in repeating the same inspection procedure. This type of *Human error* is particularly difficult to detect when a person tries to evaluate himself or herself. Human errors include common things as a tendency to read high, or low. Error sources are generally related to the capacity and skill of the individual, the human state of imperfection (inadvertent errors), and conditions that foster willful errors. With respect to willful

errors, insufficient allotment of time for inspection or some other pressure to accept product regardless of consequence may result in an inspector willfully biasing his or her techniques or results. Human errors are usually remedied as soon as they are disclosed. Personnel training is the best means of prevention of human errors.

- Errors among Operators - These are the human-related sources compounded by the number of inspectors. Two inspectors inspecting the same dimension generally obtain different results. The magnitude of such differences is proportional to the complexity of the inspection procedure. Therefore, human errors generally change with the change in observers. This is usually both due to their existence and the means for their detection.
- Errors of Materials - In those measurement systems where materials are partially consumed or deteriorate with time, errors creep in. Examples include the hardness calibration block that is partially consumed with each hardness test and the deterioration of electronic parts.
- Errors of Procedure - Each variation permitted by the inspection procedure is a possible source of error. Variations may arise from the procedure permitting the inspector to use judgment on selection of the measuring device, specific techniques for using the measuring device, and positioning or manipulation of the item to be measured. For example, if a technique developed to calibrate vernier instruments is used to calibrate micrometers, the results will have an uncertainty because the technique is not appropriate. In addition, variations may also be in the form of options spelled out in the procedure

or by the procedure specifying ranges of conditions that affect the instrument's accuracy and precision.

- Errors of Laboratory - The sources of errors listed above may be present in calibration laboratories. Each organization's calibration laboratory is susceptible to some degree of error. Also, variations of laboratory practices are possible.

Reduction of Error

If error is to be reduced, sources of error must be isolated and quantified. Elaborate test methods beyond the scope of this course are often required. While all sources of error must be considered, a specific measurement normally has only a few sources of error of sufficient magnitude to significantly affect the measurement.

As an illustration of quantified error, the precision of a hypothetical instrument is explored. Table 27-1-5 gives the results of a measurement repeated 20 times by the same instrument under the same condition with all other factors held constant. If the true value of a given parameter is 0.050, then the difference between the average of the measured values and the true value of the dimension is the error. The standard deviation of the measured values is the precision. The standard deviation is an indication of how widely the measured values are dispersed about the average measured value. Module 27-7 of this course will consider the standard deviation concept more completely. For the present, it is sufficient to say that if one computed the standard deviation for the 20 measurements listed in Table 27-1-5, its value would be 0.00176. This is a measure of just how precise the measurement is.

For purposes of illustration, then, simply consider the measured data in Table 27-1-5 as an example of determining the average measured value in comparison to the true value.

Table 27-1-5. Example of Accuracy and Precision

Measured Values

0.047	0.049	0.051	0.052
0.048	0.050	0.051	0.052
0.048	0.050	0.051	0.053
0.049	0.050	0.051	0.053
0.049	0.050	0.052	0.053

Standard Deviation - 0.00176

*** specified nominal value**

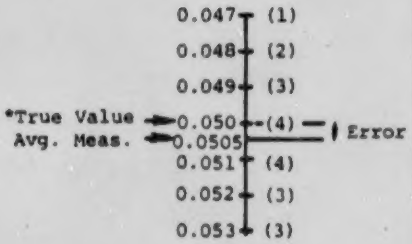


Table 27-1-5 indicates that, on the average, the instrument is inaccurate by 0.0005 inch on the high side of the true value. Calibration of the instrument to a standard would reduce this error. However, the precision is a function of the design of the instrument that calibration would not affect. Table 27-1-5 indicates that 55% of the time the instrument will repeat a measurement within one standard deviation. In this example, the instrument is fairly accurate but has poor precision.

TEMPERATURE EFFECTS

Rules for Measurements

The universally accepted standard measurement temperature is 68°F for measurement of dimensions. As measurements are made at temperatures departing from 68°F, error is introduced if differences exist in the thermal expansion of the measuring device and the item being measured. Consequently, when measurements are made at other than 68°F, the magnitude of the error is determined and, if necessary, the measurement result is corrected to account for this error. Three rules apply with respect to temperature effects on the accuracy of a measurement:

- Both the measuring device and the item to be measured must be at the same temperature.
- Measurements at 68°F do not require correction for temperature effects.
- Measurements at other than 68°F require calculation of temperature effects to determine if the magnitude of error is sufficient to warrant correction of the measured value.

Magnitude of Temperature Effects

The magnitude of the temperature effect is directly proportional to the difference in the thermal expansion coefficients of the measuring device and the item to be measured and to the amount of departure from 68°F. The temperature coefficient indicates that fraction of an inch by which each inch of length of a material changes for each degree of temperature change. Since each specific alloy has its own unique thermal expansion coefficient, the specific alloys of the measuring device and the item to be measured must be known.

For illustrative purposes only, average values of thermal expansion coefficients for some common materials are shown in Table 27-1-6. For on the job calculations, real coefficients must be used for the specific type and grade of materials. Metals handbooks and similar reference books give thermal expansion coefficients. In using these on-the-job, one should take care to ensure use of coefficients for the specific type and grade of material involved in the measurement.

Table 27-1-6. Average Thermal Expansion Coefficients

MATERIAL	COEFFICIENT
Tool Steel	6.4×10^{-6} inch/inch/$^{\circ}$F
Stainless Steel (410)	5.5×10^{-6} inch/inch/$^{\circ}$F
Tungsten Carbide	3.0×10^{-6} inch/inch/$^{\circ}$F
Chromium Carbide	4.5×10^{-6} inch/inch/$^{\circ}$F
Copper	9.4×10^{-6} inch/inch/$^{\circ}$F
Aluminum	12.8×10^{-6} inch/inch/$^{\circ}$F

As mentioned earlier, the values given in Table 27-1-6 are the average thermal expansion coefficients for various materials. On the job, it is necessary to calculate the effects of temperature on the accuracy of linear measurements, using the real coefficient for the specific type and grade of material. Temperature effects on the accuracy of linear measurements are calculated by the following formula:

$MD = L\ (k_g - k_w)(T - 68^{\circ}F)$ Equation 27-1-1

Where:

MD = measuring difference in inches of the measurement at temperature as compared to the same measurement at $68^{\circ}F$.

L = length of the measurement in inches.

k_g = thermal expansion coefficient of the measuring device in inch per inch of length per $^{\circ}F$.

k_w = thermal expansion coefficient of the workpiece in inch per inch of length per $^{\circ}F$.

T = temperature in $^{\circ}F$ at which the measurement is made.

EXAMPLE:

Problem: What is the value of the measurement corrected to $68^{\circ}F$?

Given: A measurement at $58^{\circ}F$ of an aluminum bar with a steel device reads 84.125 inches.

Solution:

$$MD = L\ (k_g - k_w)(T - 68^{\circ}F)$$

$$= 84.125\ (6.4 \times 10^{-6} - 12.8 \times 10^{-6})(58 - 68)$$

$$= 84.125\ (-6.4 \times 10^{-6})(-10)$$

$$= 5384 \times 10^{-6} \text{ inch} = 0.005384 \text{ inch}$$

$$\text{value at } 68^{\circ}F = 84.125 + 0.005$$

$$= 84.130 \text{ inches}$$

NOTE: If MD is a negative value, it is subtracted from L.

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CLEANLINESS

Importance of Cleanliness

Cleanliness is absolutely necessary if accurate dimensional inspection is to be achieved. Both the measuring device and the item to be inspected must be clean. Otherwise, accuracy and precision of the measurements are affected. The concern for this effect increases as the need for accuracy increases. For example, cleanliness is a larger factor when accuracy must be within 0.001 inch than when it must be within 0.010 inch.

Sources of errors from a cleanliness viewpoint include dirt, lint, scale, rust, oil, grease, paint, ink or chalk markings, and any other loose surface materials. Where highly accurate measurements are required on an on-going basis, clean rooms are established to maintain a state of cleanliness. Such clean rooms are enclosed and have filtered air supplies and a schedule for cleaning all surfaces. Temperature and humidity control are also normally provided in clean rooms. Where such high accuracy is necessary but the item cannot be transported to a clean room, a temporary clean room or area is constructed around the item. Regardless of whether a clean room is used, *measuring devices and items to be inspected are always cleaned prior to inspection.* (CAUTION: Cleaning may cool the items; time should be allowed for temperature equalization.)

CARE AND HANDLING OF INSTRUMENTS

Importance

Proper care and use of instruments cannot be stressed enough. The various gages are sensitive instruments whose accuracy is adversely affected by abuse. All users of gages must properly use and care for gages and when an instrument is inadvertantly mishandled, turn it in to the calibration laboratory for checking and recalibration.

Guidelines for Care and Handling

Users of instruments must know how to properly handle and care for the instrument in order to maintain it in its "calibrated" condition. Regardless of the type of instrument, the following guidelines provide for proper care and handling:

- Use the instrument only for the purposes for which it is intended.
- Never use any manipulative device or force the instrument.
- Clean and remove burrs prior to use.
- Never expose an instrument directly to heat.
- When an instrument has been exposed to heat, be sure the expansion caused by heat does not exceed tolerance.
- Avoid exposure to dust, moisture, and grease,
- Lightly oil instruments and store in a protected case or cabinet.
- Return all instruments to storage case or cabinet after use.

EXERCISES

Briefly explain or discuss each of the following concepts covered in this module:

1. Metrology is a science of measurement that is absolutely necessary to insure the fit, function and interchangeability of product.
2. Measurement is impossible without standards.
3. Standards are the embodiment or true value of units of measurement and the written criteria governing an inspection procedure.
4. Transfer and working standards permit all organizations making measurements to employ standards which are traceable to the primary reference standards of the U.S. National Bureau of Standards.
5. The principal concepts associated with measurement are standards, accuracy and precision.
6. The accuracy of a specific measuring device is a function of its design and its readability, sensitivity and linearity.
7. The 4 to 1 rule states that the measuring device should have discrimination and sensitivity that is no more than 25% of the tolerance of the dimension to be measured.
8. Error can stem from any portion of the measurement procedure. Normally, only one or two sources of error are of such magnitude as to be of significant concern.
9. Accuracy and precision of measurement are directly proportional to the state of cleanliness of the instrument and the item to be measured.
10. Three rules apply to measurements with respect to temperature effects:
    a. Both the measuring device and item to be measured must be the same temperature.

b. Measurements at 68°F do not require correction for temperature effects.

c. Measurements at other than 68°F require calculation of temperature effects to determine if the magnitude of error is sufficient to warrant correction of the measured value.

11. For linear measurements, the temperature effects are calculated by the formula $MD = L\ (k_g - k_w)\ (T - 68°F)$.

MATERIALS

The following materials are required to support this module:

1. Laboratory Vee Blocks
2. Steel Rules (12 inches minimum)
3. Wood Rules (12 inches minimum)
4. Length Standard (gage block set or calibrated scale)

PROCEDURES

The following activities reinforce the information presented in this module:

Given:

Laboratory Vee Block
12 inch Steel Rule
12 inch Wood Rule

Perform the following:

1. Measure the width of the Vee Block ten times each with wood and steel rules. Record values in a table.
2. Calculate the average value of each set of ten readings

$$\bar{x} = \frac{x_1 + x_2 + \text{-----} x_{10}}{10}$$

3. Measure the width of the Vee Block using different sections of the rule. For example, if the 0 to 4 inch portion was initially used, measure with the 4 to 8 inch and 8 to 12 inch portions. Record any differences from the initial values.
4. From the initial measurements, state possible reasons for any of the following conditions that resulted:
   - Differences between readings of the steel rule and the wood rule.
   - Differences in readings of the same rule.
5. Compare the steel rule to a standard (either another steel rule or a gage block). State similarities and differences.
6. Compare the measurements obtained in step 1 with those obtained in step 3. State similarities and differences and describe linearity of the rule.
7. List the factors that affect the rules' readability and sensitivity.
8. Describe the primary standard, the transfer standard and the working standard for the measuring device you have used.

DATA TABLE

Data Table 27-1-1

Measurement of Vee Block

	Measurements with Wood Rule	Measurements with Steel Rule	Other Measurements
1.			
2.			
3.			
4.			
5.			
6.			
7.			
8.			
9.			
10.			
Sum			
Average			

Description of Reason for Differences in Measurements: ____

____

____

Comparison of Steel Rule with Standard: ______________

____

____

Linearity of Rule: ______________________________

____

Description of Standards: ________________________

____

REFERENCE MATERIALS

Brown and Sharpe Mfg. Co., *Principles and Practice of Precision Measurement*, Brown and Sharpe Mfg. Co., Precision Park, North Kingstown, RI, 1975

Busch, Ted, *Fundamentals of Dimensional Metrology*, Delmar Publishers, Third Edition, 1966

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J.M. Juran, *Quality Control Handbook*, McGraw-Hill Book Company, New York, N.Y., Third Edition, 1974

Society of Manufacturing Engineers (SME), *Handbook of Industrial Metrology*, Prentice-Hall, Inc., 1967

U.S. Department of Commerce, *Letter Circular LC1035, Units and Systems of Weights and Measures; Their Origin, Development and Present Status*, National Bureau of Standards, Washington, D.C. 20234

TEST

Define the following:

1. Standard:

   Accuracy:

   Linearity:

   Sensitivity:

   Readability:

   Precision:

   Measurement:

2. Why is it necessary for metrology to be applied to the design, construction and operation of nuclear power plants?

3. Briefly describe each of the following standards and name the type standard to which each is compared for accuracy.
   a. Working Standards:

   b. Primary Reference Standards:

   c. Transfer Standards:

   d. Measuring Instruments & Equipment:

4. Why are standards important to measurement? How are standards adopted?

5. Name and state the major function of the three common design features that all measuring instruments or devices have.
   a.

   b.

   c.

6. Why is accuracy an important characteristic of a measuring device? What two principles govern the accuracy of a measurement?

7. Name four factors that affect the precision of a measurement process.
   a.
   b.
   c.
   d.

8. What is tolerance? Why is the tolerance-to-readability ratio used?

9. Name four factors that affect the sensitivity of a measuring instrument.
   a.
   b.
   c.
   d.

10. Name three factors that affect a measuring instrument's linearity.

a.

b.

c.

11. Name two factors that affect a measuring device's readability.

a.

b.

12. Name six sources of errors of measurement. Describe the factors that contribute to each source of error.

a.

b.

c.

d.

e.

f.

13. Why is it necessary to calculate temperature effects when measurements are made at temperatures above or below 68°F?

14. Find the value of the measurement, corrected to 68°F, given the following (use the average thermal expansion coefficient of 9.4×10^{-6} inch/inch/°F for copper and 6.4×10^{-6} inch/inch/°F for tool steel).

Feature: length of copper spacer bar
Instrument: tool steel outside micrometer
Temperature: 83°F
Measured Value: 12.4485 inches

Use the scale below to give the value, in inches, of questions 15-21.

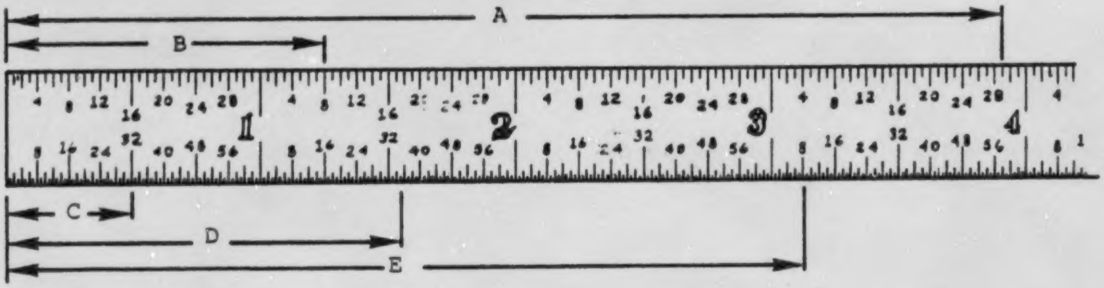

Figure 27-1-6

15. Discrimination of top scale ____________________

16. Discrimination of bottom scale ____________________

17. A length = ____________________

18. B length = ____________________

19. C length = ____________________

20. D length = ____________________

21. E length = ____________________

NUCLEAR TECHNOLOGY

MODULE 27 - 2

FIXED GAGES, DIVIDERS, CALIPERS AND MICROMETERS

COURSE 27: METROLOGY

CORD

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 27 METROLOGY

MODULE 27-1	Fundamentals of Metrology
⇨ MODULE 27-2	Fixed Gages, Dividers, Calipers and Micrometers
MODULE 27-3	Gage Blocks, Mechanical Comparators and Electronic Comparators
MODULE 27-4	Angle Measurement Instruments, Optical Projectors and Surface Texture Gages
MODULE 27-5	Tolerancing
MODULE 27-6	Calibration
MODULE 27-7	Statistical Techniques in Metrology
MODULE 27-8	The Total Measurement System

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INTRODUCTION

Many different types of measuring devices are available for use in dimensional inspection. The primary factors involved in selection of the "best" device are the type of dimension to be measured, the tolerance of the dimension and the characteristics of the measuring device. Modules 27-2, 27-3 and 27-4, describe various types of measuring devices, their typical applications and sources of errors in measurements with each type. Module 27-5 describes tolerancing methods. Then, after discussion of calibration and sampling techniques in Module 27-6 and 27-7, the total measurement system is described in Module 27-8. Therefore, this module and the subsequent ones lay the foundation of the total measurement system is described by Module 27-8.

This module describes fixed gages, dividers, calipers, vernier and dial calipers, and micrometers. The student/trainee should give particular attention to the application and sources of error with these instruments. Also, the student/trainee should practice making measurements with these instruments to develop skill in measuring with accuracy and precision.

MODULE PREREQUISITES

The student/trainee shall have completed Module 27-1.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. Given a type of divider, caliper, vernier, micrometer or fixed limit gage, name at least one typical use of the instrument.
2. Given a type of divider, caliper, vernier, micrometer or fixed limit gage, name at least three sources of error in measurements with the instrument.
3. Define a GO and NOT GO limit gage and describe the differences between master fixed gages and limit fixed gages.
4. Demonstrate the ability to interpret Unified System thread designators.
5. Demonstrate the ability to make measurements with dividers, calipers, verniers, micrometers, and fixed limit gages, and to determine sources of errors in these measurements.

NOTES TO INSTRUCTOR / STUDENT

Laboratory exercises are recommended to develop student/trainee skills in making measurements with the instruments described in this module. The module includes suggested exercises and procedures for this purpose although the instructor will need to tailor these to local circumstances. Advance preparation will be necessary to provide for a selection of parts to be measured: (Suggested parts are included in the activities and materials of this module.); the instruments to be used: (Suggestions are included in the activities and materials of this module); standards to be used and whether the student/trainee or the instructor will apply the standard for accuracy checks.

SUBJECT MATTER

FIXED GAGES

Fixed Gages

Fixed gages do not measure actual size but merely determine whether work pieces are within limits of tolerance. Fixed gages are classified as either master gages or limit gages. The master gage is manufactured to represent the dimension to be measured. In this capacity, the master gage serves as a standard for calibrating other instruments. The limit gage is manufactured to represent the limit of a toleranced dimension. In this role, the limit gage is an inspection device. Two limit gages are necessary. One for measuring one extreme of the tolerance and the other for measuring the other extreme. However, both measurement surfaces may be integral with one instrument.

Principles of Limit Gage Measurements

Limit gages are made to sizes essentially identical to the tolerance limits of the dimension to be inspected. The accuracy in being identical to the tolerance limits is based on standard gage makers tolerances, which classify gages by their accuracy. For example, Table 27-2-1 lists gage makers tolerances for cylindrical plug and ring gages.

Table 27-2-1 Gage Maker Tolerances for Cylindrical Plug and Ring Gages

RANGE AND TOLERANCES					
Size Range		Class XX	Class X	Class Y	Class Z
Above	To and Including				
0.29	0.825	0.00002	0.00004	0.00007	0.00010
0.825	1.510	0.00003	0.00005	0.00009	0.00012
1.510	2.510	0.00004	0.00008	0.00012	0.00016
2.510	4.510	0.00005	0.00010	0.00015	0.00020
4.510	6.510	0.000065	0.00013	0.00019	0.00025
6.510	9.010	0.00008	0.00016	0.00024	0.00032
9.010	12.010	0.00010	0.00020	0.00030	0.00040

Whenever a specific limit gage can enter an inside dimension or an outside dimension can enter the limit gage, the measured dimension will assemble with a mating part whose boundaries are equal to those of the gage. The conclusion is that the part will "go" at assembly and, hence, the designation of this limit gage as the GO gage. The GO gage is defined as a limit gage that contains the reverse physical replica of the dimension to be measured at its maximum permissible material condition. That is to say, when determining the *reverse physical replica* of the dimension to be measured, it should be realized that for determining whether a cylindrical hollow tube is of the proper inside diameter, a solid cylindrical rod could be inserted to verify that the tube dimensions are proper.

In similar manner, if a cylindrical rod outer diameter is to be verified, a hollow cylindrical tube could be used as the *reverse physical replica* for this measurement.

For outside dimensions, the GO gage equals the maximum permissible size of the dimension to be inspected. For an inside dimension, the GO gage equals the minimum permissible size of the dimension to be inspected. Under each of these circumstances, maximum material is present.

In addition to assuring assembly, the function of the assembled parts is dependent on the tightness of assembly. Therefore, the minimum material condition has limits intended to assure the proper function of the parts. If a limit gage is made to coincide with the minimum material condition, an acceptable part should not enter the gage or the gage should not enter the acceptable part. The NOT GO gage is defined as a limit gage that contains the reverse physical replica of the dimension to be measured at its minimum acceptable material condition. Thus, for outside dimensions, the NOT GO gage equals the minimum permissible size of the dimension to be inspected. For inside dimensions, the NOT GO gage equals the maximum permissible size of the dimension to be

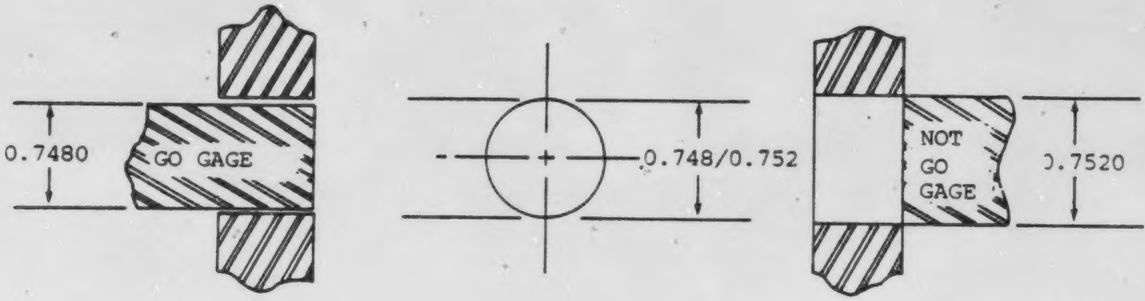


Figure 27-2-1. Product Features as measured by a GO and NOT GO gage.

inspected. In each case, the dimension is at the minimum material condition. The use of GO and NOT GO limit gages for an inside dimension is illustrated in Figure 27-2-1.

A typical example of a GO and NOT GO gage is shown in Figure 27-2-2. In this figure, the GO plug should enter the hole in the part and the NOT GO plug should not. However, when making measurements one should be aware of the fact that every single time any gage or measurement instrument is used it wears. Also, everytime a part is measured it wears. This wear is very minor, but it is definitely measureable, and must be taken into consideration. This particular fact is often misunderstood. For example, literally tens of thousands of very expensive class XX plug gages are purchased every year for applications where they wear into class X tolerance gages within the first few minutes of use. The moderately priced class X gages could have been bought in the first place. Wear is so important that it is recognized in the specifications of gages that have been standardized. It is called the wear allowance. Those who go into industrial measurement will become well acquainted with it. Figure 27-2-2 also shows the wear allowance on the GO plug denoting that it reduces the tolerance specified for the hole to be measured.

Limit Gage for Length Dimension

The snap gage and the limit length gage are two common limit gages for measuring outside length dimensions. These gages often contains adjustable measurement surfaces to permit setting the gage with a master within a range of GO and NOT GO limits. Rather than requiring two gages, GO and NOT GO features are normally contained by a single gage. Gage sizes range from about 1/8 of an inch to 40 inches. Figure 27-2-3 illustrates these two gages.

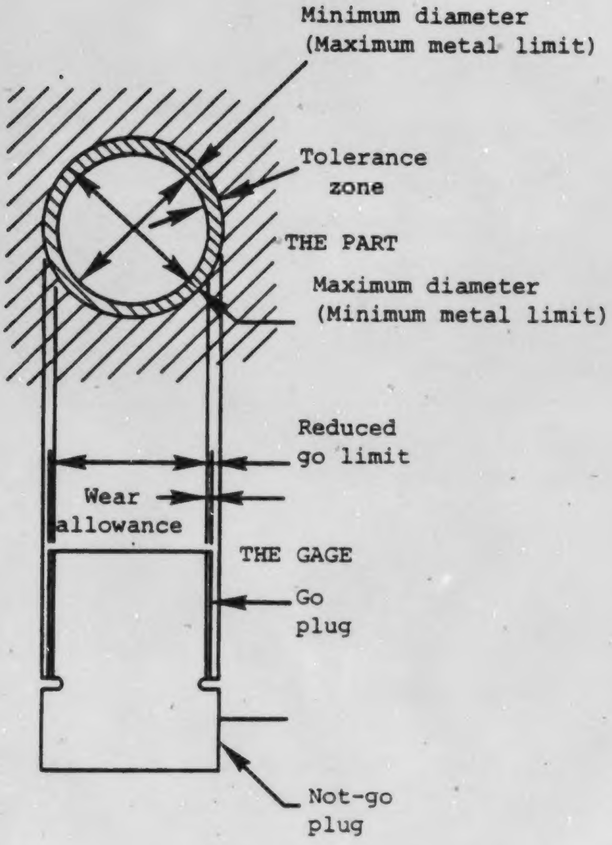
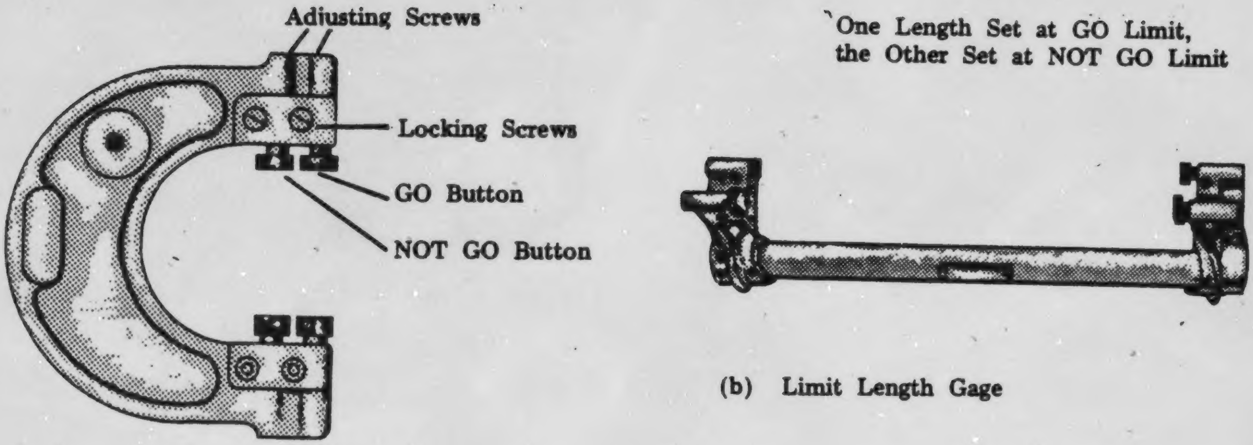

Minimum diameter
(Maximum metal limit)
Tolerance zone
THE PART
Maximum diameter
(Minimum metal limit)
Reduced go limit
Wear allowance
THE GAGE
Go plug
Not-go plug

Figure 27-2-2. The GO plug should enter the hole in the in the part. The NOT GO plug should not. The wear allowance on the GO plug reduces the tolerance specified for the hole.


Adjusting Screws
Locking Screws
GO Button
NOT GO Button
One Length Set at GO Limit, the Other Set at NOT GO Limit

(b) Limit Length Gage

(a) Limit Snap Gage

Figure 27-2-3. Outside Length Limit Gages

The snap gage is a set of fixed calipers and can be used in checking most outside dimensions where a micrometer might be used. In long production runs, it has a distinct advantage over the more familiar mike, in that it does not have to be adjusted and read out each time it is used. The outer gaging button, where the workpiece enters the gage, is set at the GO dimension. That is the distance between the adjustable and the fixed anvils must be equal to - or slightly less than - the maximum dimension permitted by the part tolerance. The inner button is set to the NO GO or minimum dimension. Thus, the GO-NO GO test is quick and easy. A workpiece in tolerance will pass the outer pin and stop at the inner pin. An oversize piece will not enter and an undersize piece will pass under both pins, as shown in Figure 27-2-4.

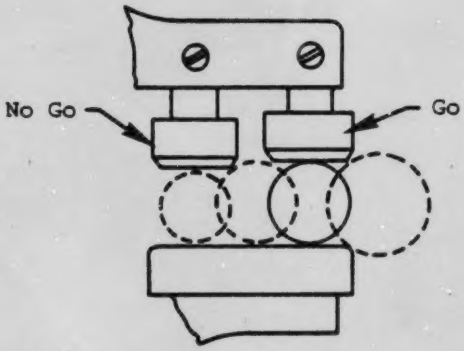


Figure 27-2-4. Use of the Snap Gage.

Limit plug gages are fixed gages for measure inside lengths between flat, parallel surfaces or inside diameter of large bores. The contact surfaces are spherical for bore measurements. Two styles of these gages are shown in Figure 27-2-5. The style in detail (a) is made in sizes from about 2 1/2 to 4 1/2 inches. The style in detail (b) is made for larger sizes up to about 12 inches.

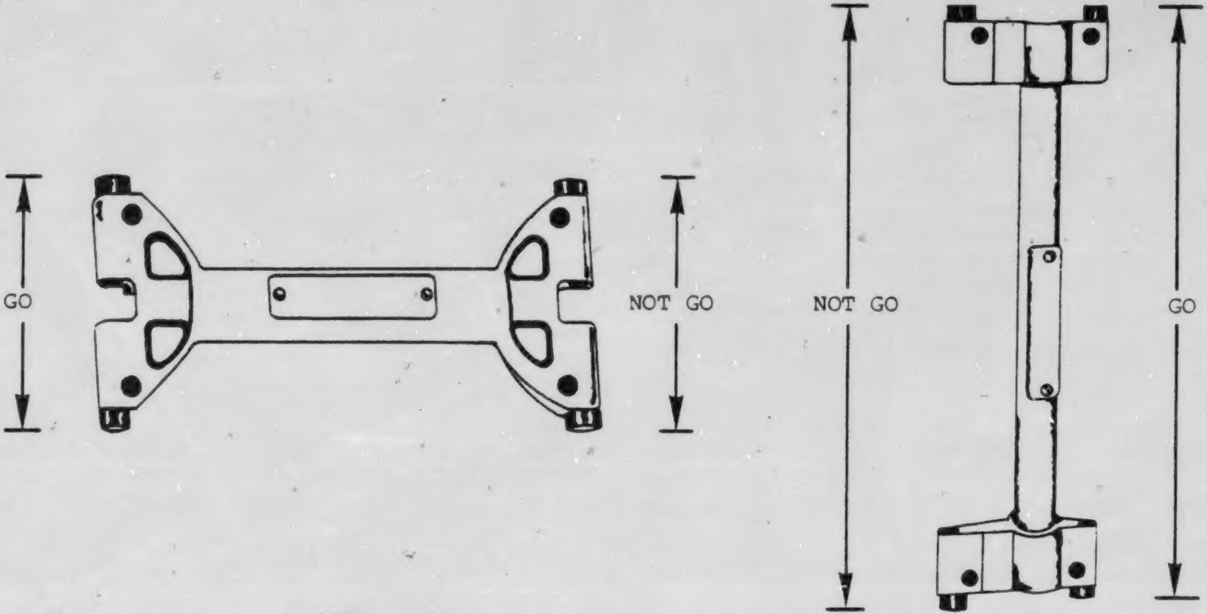
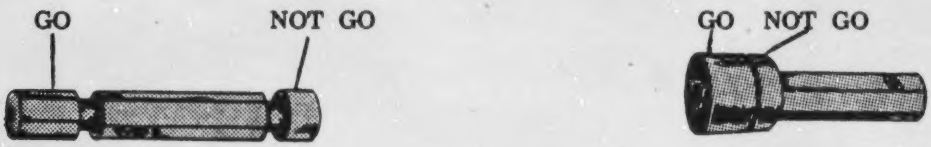


Figure 27-2-5. Inside Length Limit Gages

Cylindrical Limit Gages

Measurement of the diameter of a cylindrical part pertains to a single length dimension. But the diameter probably varies at different degrees of rotation and at different lengths (depths) of the cylinder. The effective size of the cylinder includes the form of the cylinder, i.e., its roundness and cylindricity. Cylindrical limit gages are designed to measure not only the diameter but the form of a cylindrical part.

Cylindrical Plug Gages are used for measurement of round holes. They can also be used for gaging slot widths between parallel walls. Most cylindrical plug gages have the GO and NOT GO members mounted on the same handle to permit gaging both limits with one device. Figure 27-2-6 illustrates the double ended cylindrical plug gage in detail (a) and the progression cylindrical plug gage in detail (b).



(a) **Double - Ended**

(b) **Progressive**

Figure 27-2-6 Cylindrical Plug Gages

The GO section in each is longest because an acceptable bore must accept the GO gage the full depth of the bore. Various designs of cylindrical plug gages permit measurement between about 0.030 inch to 12 inches.

Cylindrical Ring Gages

The counter-part of the cylindrical plug gage is the cylindrical ring gage. The cylindrical ring gage measures the outside form of a basically round shaft. These gages are used in lieu of snap and length gages when the effective diameter of the part is to be measured. Separate GO and NOT GO cylindrical ring gages are used for measurement. This permits moving the GO ring gage the entire length of the shaft. The two are distinguishable by a groove on the NOT GO cylindrical plug gage as shown in Figure 27-2-7. It is noted that the GO cylindrical ring gage is not a good indicator of roundness and the NOT GO measurement is made only at the end of the shaft.

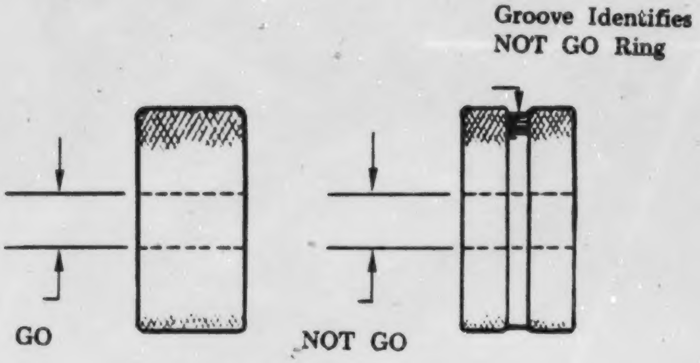


Figure 27-2-7. Cylindrical Ring Gages

It should be pointed out that the NOT GO rings and plugs do not inspect a diameter in the same sense as the GO members. When they fail to engage the part, it claimed to be in size *by agreement* between contractors. Actually it is possible, for example, that a shaft may be larger on the ends than it is in the middle. Or it may be slightly out-of-round. These conditions would not be detected. As the need for precision increases, the NOT GO check becomes less satisfactory and the results should be spot-checked by some other means, such as a micrometer or a snap gage. Some quality control departments order their NOT GO plugs flatted and their rings relieved as shown in figure 27-2-8, so that the diameter is checked in small segments. An out-of-round condition can often be detected by rotating such a gage.

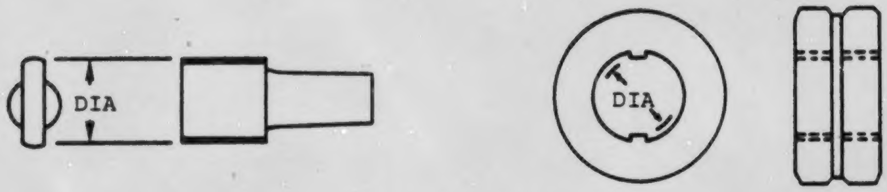


Figure 27-2-8. Modified NOT GO Gages for checking out of round conditions.

Fixed Gages for Multiple Dimensions

There are certain standardized parts having forms consisting of several dimensions that establishes their actual size. A threaded fastener is a good example of such a part where the major, minor and pitch diameters, threads per inch, lead angle, and thread form all affect the effective size. Envelopes of acceptable sizes of such parts can be calculated based on the cummulative effect of tolerance of individual dimensions. Fixed gages are sometimes used to measure such an envelope of tolerances.

Thread limit gages are comprised of thread plug gages for measurement of thread holes and thread ring gages for measurement of threaded shafts. Design of these gages is based on standardized thread designs of the Unified System illustrated in Figure 27-2-9.

Thread limit plug and ring gages are available in the same range of sizes as the cylindrical plug and ring gages. As illustrated in Figure 27-1-10, thread plug gages are fixed and thread ring gages can be of an adjustable design. The adjustable thread ring gage is set with a master thread plug gage of the desired thread form. GO thread gages check the maximum material size. HI and LO thread gages check the minimum material size. In use, the GO gage must engage the thread for its entire length while the HI or LO gage must result in a definite drag on or before engagement of the third thread. (Gages should never be forced.)

Roll thread snap gages provide a faster method of inspecting external threads that is offered by thread limit ring gages. The gage jaws of the roll thread snap gage are pairs of free-turning rolls comprised of annular rings, i.e., they are not cut in a helix like a screw thread. The GO rolls have full thread profile for checking the maximum material condition of threads. The NOT GO rolls are truncated and check the pitch diameter at minimum material condition.

Tapered threads are checked with a roll-type set at the desired taper. Tapered roll thread gages are available for checking both internal and external threads. For acceptance of external tapered threads, the gage must thread onto the part until the face of the gage is flushed with the end of the threaded portion of the work piece as shown in Figure 27-2-11. Falling short or exceeding the flush condition results in the rejection of the tapered external thread.

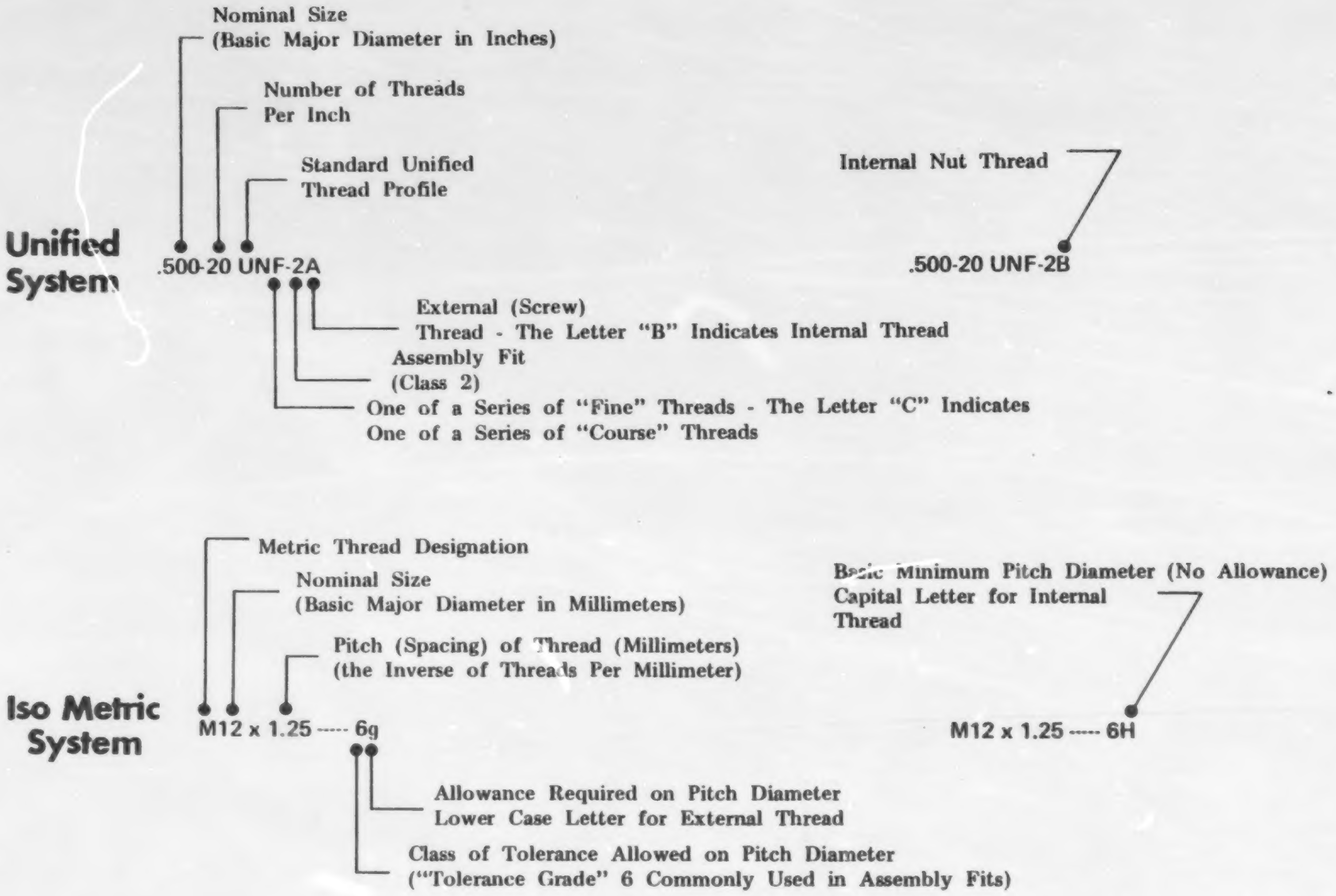

Unified System
Nominal Size
(Basic Major Diameter in Inches)
Number of Threads
Per Inch
Standard Unified
Thread Profile
.500-20 UNF-2A
External (Screw)
Thread - The Letter "B" Indicates Internal Thread
Assembly Fit
(Class 2)
One of a Series of "Fine" Threads - The Letter "C" Indicates
One of a Series of "Course" Threads
Internal Nut Thread
.500-20 UNF-2B
Iso Metric System
Metric Thread Designation
Nominal Size
(Basic Major Diameter in Millimeters)
Pitch (Spacing) of Thread (Millimeters)
(the Inverse of Threads Per Millimeter)
M12 x 1.25 ----- 6g
Allowance Required on Pitch Diameter
Lower Case Letter for External Thread
Class of Tolerance Allowed on Pitch Diameter
("Tolerance Grade" 6 Commonly Used in Assembly Fits)
Basic Minimum Pitch Diameter (No Allowance)
Capital Letter for Internal
Thread
M12 x 1.25 ----- 6H

Figure 27-2-9. Thread Designation Systems

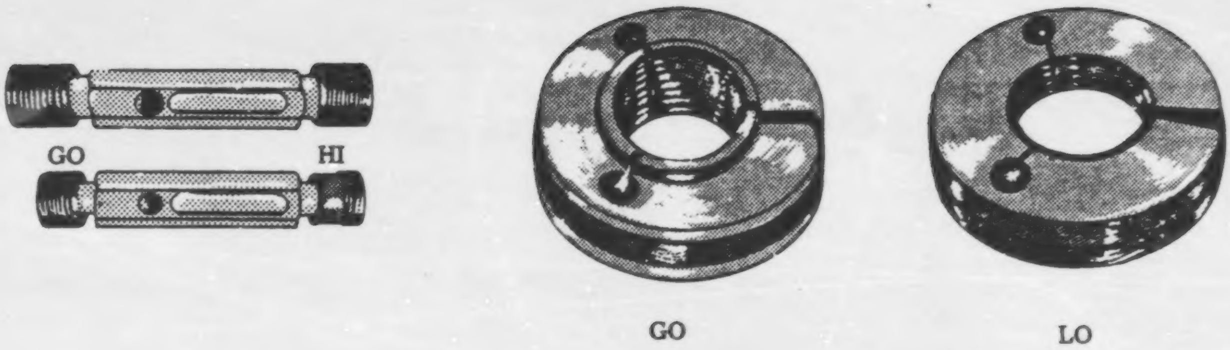
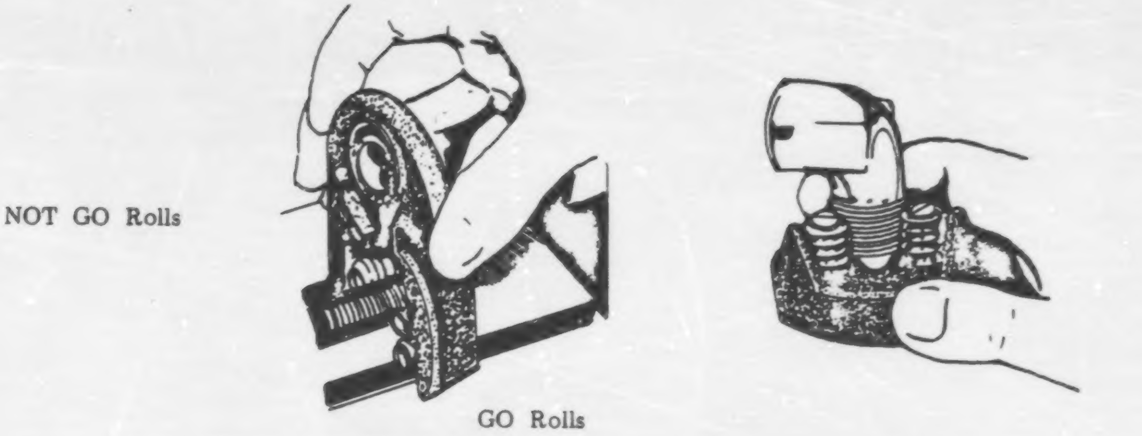


Figure 27-2-10 Thread, Plug and Ring Gages



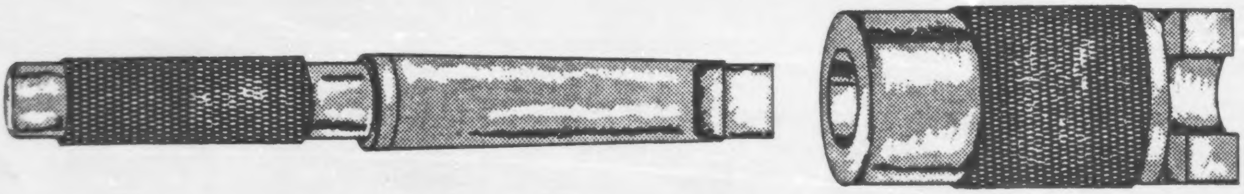
a. Roll Thread Snap Gauge

b. Tapered Roll Thread Gauge

Figure 27-2-11 Roll Thread Gauges

For internal tapered threads, the gage has a flat or scribe mark which denotes the position to which the gage should enter the tapered, tapped hole. Entry of the gage short of or beyond the flat or mark results in rejection of the part.

Taper plug and ring gages are used for measurement of tapered bores and shafts respectively. The taper is normally of concern from a reference diameter. Therefore, the taper plug and ring gages are scribed or grooved at the reference diameter. Since tapers are used for snug or press fits at assembly, the taper plug or ring gage should not wobble when placed to the reference diameter. Prussian blue may also be used. If the bluing is uniform over the workpiece or instrument, the tape is acceptable, Figure 27-2-12 pictures taper plug and ring gages.



Taper Plug

Taper Ring

Figure 27-2-12. Taper, Plug and Ring Gages

Accuracy and Precision of Fixed Gages

The manufacturing tolerances and stability of materials have the largest effect on the inherent accuracy of fixed gages. Wear of mating surfaces during use of these gages will deteriorate accuracy as was discussed previously regarding GO and NOT GO gages.

The most important inspector's techniques pertain to cleanliness of the gage and workpiece and "feel" of the gage. Small amounts of dirt or other foreign material can cause erroneous rejection of good parts or acceptance of bad parts.

The "feel" of the gage includes proper positioning (similar to positioning the micrometer) and pressure applied to the GO and NOT GO members. In general, fixed limit gages should "go" or "not go" with finger pressure. If the muscles of the arm are being used to force the gage, too much pressure is being applied.

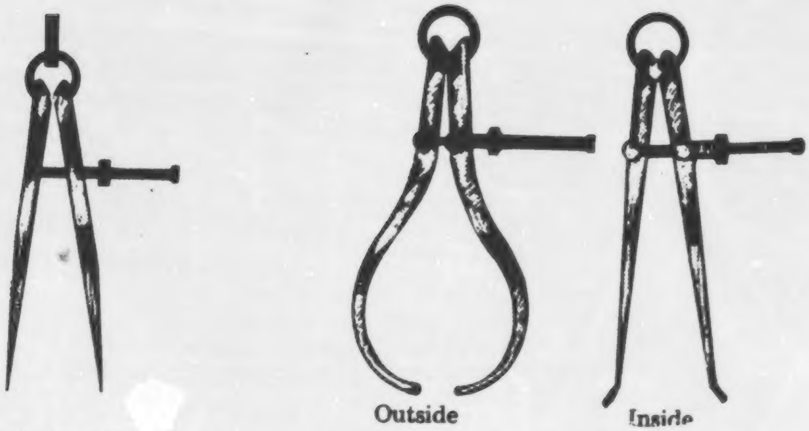
The accuracy and precision of measurement with the fixed limit gage is primarily dependent on the inspector's feel. For this reason, and because quantitative data is not generated for process control, fixed limit gages used in the inspection of items for nuclear power plants is mostly limited to cylindrical plug and ring gages and thread plug and ring gages. Taper and spline plug and ring gages see some use.

CALIPERS AND DIVIDERS

Description

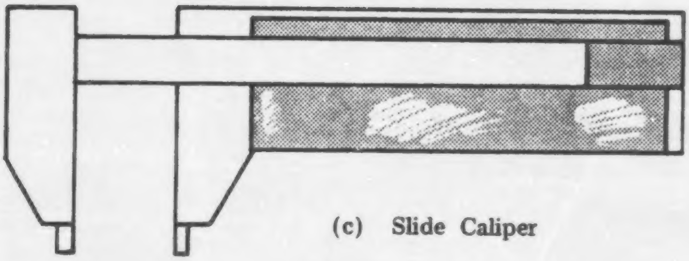
Calipers and dividers are types of transfer devices that require supplementary gaging or modified design to give a readout. Basic types of calipers and dividers are shown in Figure 26-2-13.

All of the devices shown in Figure 27-2-13 are purely transfer devices, i.e., they do not contain a self contained readout. More sophisticated designs of these instruments add a line-graduated scale that permits direct readout. The most common of these with direct readout is the slide caliper. It is not difficult to envision a scale along the beam of the slide caliper in Figure 27-2-13 that would give a direct readout. Since such direct reading slide calipers are normally also equipped with a second scale (vernier), they are discussed later in this module.



(a) Divider

(b) Point Calipers



(c) Slide Caliper

Figure 27-2-13 Divider, Pointer Calipers, Slide Calipers

Application

Dividers and calipers are used for measurement where accuracy and precision requirements are equal to that of the steel rule. These devices essentially eliminate the major source of error of the rule, i.e., alignment of the length boundaries with the graduations of the rule.

The divider provides for point measurement. One tip is placed at a point of one boundary and the span of the divider is adjusted such that the other tip is at the point of the other boundary. The thumb nuts permit clamping of the dividers at the span setting. Common uses of the divider include scribing circles and arcs, establishing center points for center punching, and measuring distances between reference points or lines. Figure 27-2-14 shows dividers being used to find the center of a steel shaft.

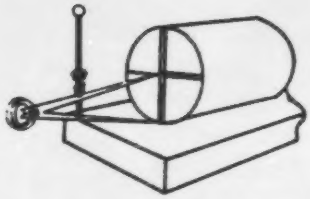


Figure 27-2-14 Dividers being used to find center of shaft. (South Bend Lathe)

The outside caliper is used primarily for measuring outside diameters of cylindrical parts (solid or hollow) as shown in Figure 27-2-15.

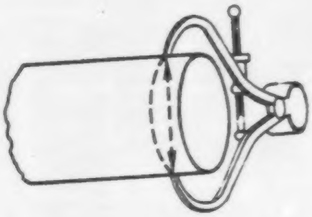


Figure 27-2-15 Measuring diameter of shaft, using an outside caliper. (South Bend Lathe)

The inside caliper is used primarily for measuring inside diameters of bored or drilled holes or hollow cylindrical parts as shown in Figure 27-2-16.

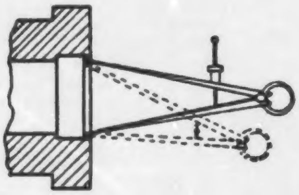


Figure 27-2-16 Using inside caliper to measure diameter of counterbore.

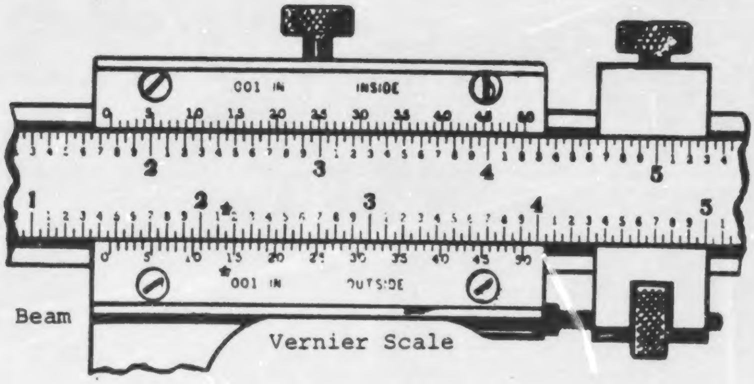
Again, the thumb nuts permit clamping of the calipers at the span setting.

The slide caliper is used for measuring lengths and diameters where the tips of the jaws can be fitted against the boundaries. Jaws of most slide calipers permit both inside and outside fitting against the measurement boundaries.

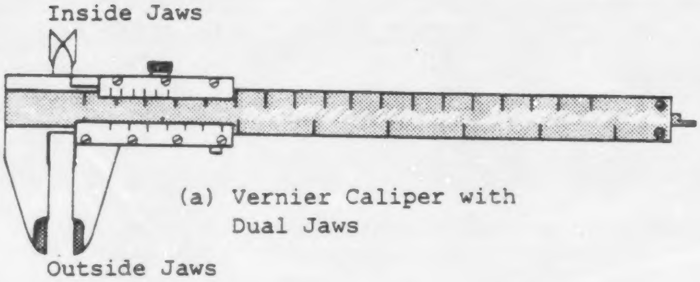
VERNIER AND DIAL CALIPERS

Description of Vernier Calipers

Vernier calipers are designed around the principle of a graduated bar with a stationary jaw and a movable jaw. The primary scale is scribed on the beam of the stationary jaw. To the movable jaw, a vernier scale added. The caliper is normally equipped with a fine-adjustment feature that permits a more uniform "feel" of pressure on the tips of the jaws. On standard vernier calipers, both inside and outside readings are taken from the same set of jaws. On others, two sets of jaws are provided. Verniers are available with both inch and centimeter units. Vernier plates are available with either a 25- or 50- division scale. Figure 27-2-17 pictures a vernier caliper with separate sets of jaws for inside and outside measurements. It also shows a close-up of a 50 division vernier scale. In the close-up view, the fine adjust and set screws are clearly visible.


.001 IN
INSIDE
0 5 10 15 20 25 30 35 40 45 50
2 3 4 5
1 2 3 4 5
0 5 10 15 20 25 30 35 40 45 50
.001 IN
OUTSIDE
Beam
Vernier Scale

(b) Vernier Scale


Inside Jaws
Outside Jaws

(a) Vernier Caliper with Dual Jaws

Figure 27-2-17 Vernier Caliper

Reading the Vernier Caliper

Reading the vernier caliper is explained based on the vernier scale shown in Figure 27-2-17(b). The upper scale is used in conjunction with measurements with the inner jaws. The lower scale is for measurements with the outer jaws. The lower scale is explained; reading the upper scale is similar.

The basic reading on the beam is at the zero point of the vernier. When this zero does not coincide with a division on the beam, the graduation value on the beam immediately preceding the vernier zero is supplemented by a value obtained from the vernier. The supplementary value is the value of the vernier that exactly aligns with any of the graduations on the beam. Thus, the total value of the vernier is equal to the value of one graduation on the beam. The principles used in reading the vernier scale will apply to any vernier instrument. Ted Busch[1] outlines a technique for reading a vernier scale. The discussion which follows discloses the essence of his technique.

Consider a vernier scale measuring length in inches. The main scale is divided into inches. Each inch is divided into inches. Each inch is divided into ten parts, and each of these divisions is subdivided into quarters, as shown in Figure 27-2-18. The smallest divisions are thus 1/40 in. One thousand divided by 40 is 25; therefore the smallest divisions are 0.025 in. and read as units of 25 *mil*. Note that from its start, the vernier has been a decimal instrument, not fractional.

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[1] Ted Busch, Fundamentals of Dimensional Metrology, Delmar Publishers

READING A VERNIER IN INCHES

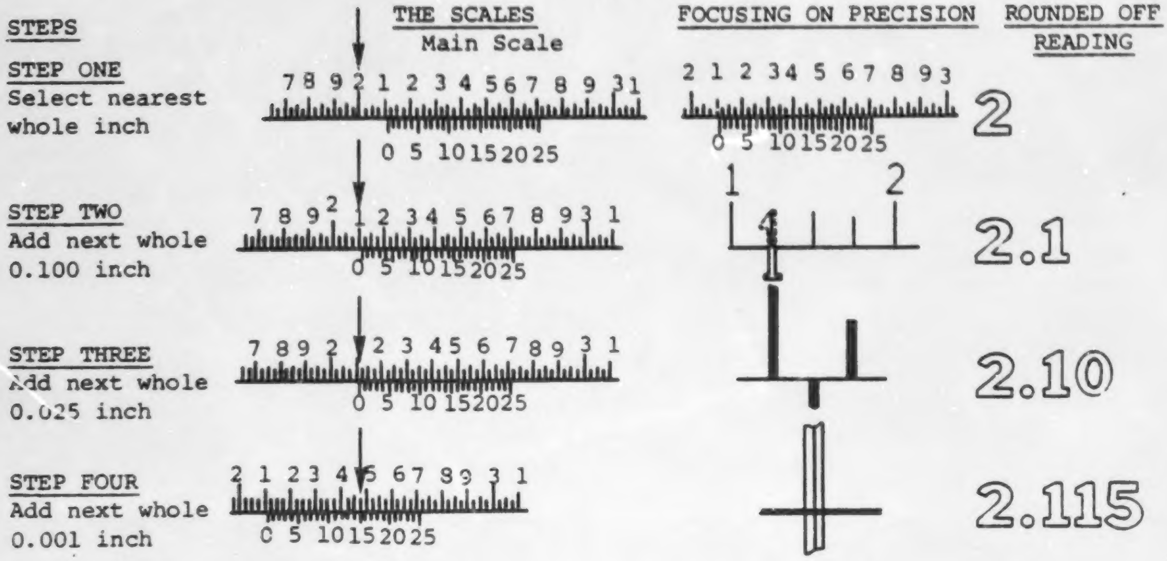
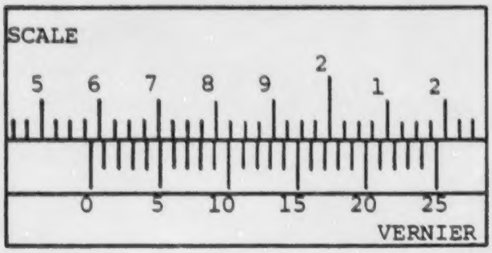

STEPS
THE SCALES
Main Scale
FOCUSING ON PRECISION
ROUNDED OFF READING
STEP ONE
Select nearest whole inch
7 8 9 2 1 2 3 4 5 6 7 8 9 3 1
0 5 10 15 20 25
2 1 2 3 4 5 6 7 8 9 3
0 5 10 15 20 25
2
STEP TWO
Add next whole 0.100 inch
7 8 9 2 1 2 3 4 5 6 7 8 9 3 1
0 5 10 15 20 25
1
2
2.1
STEP THREE
Add next whole 0.025 inch
7 8 9 2 1 2 3 4 5 6 7 8 9 3 1
0 5 10 15 20 25
2.10
STEP FOUR
Add next whole 0.001 inch
2 1 2 3 4 5 6 7 8 9 3 1
0 5 10 15 20 25
2.115

Figure 27-2-18 Reading a Vernier in Inches

Each of the steps for reading a vernier raises the results to a higher level of precision, much like focusing a microscope.

In a caliper the vernier scale is attached to the sliding jaw and moves along the main scale. It has 25 divisions in the same length that the main scale has 24. The difference between a main scale division and a vernier division is 1/25 of a main scale division. Hence, 1/25 of 0.025 in. is 0.001 in. or *one mil*. This is the discrimination of the instrument, and is called the *least count*. A vernier is read by adding the total readings from the main scale to the thousandths readings on the vernier scale. This applies to the controls on machines as well as scales on instruments, as shown in Figures 27-2-18 and 27-2-19.



FROM A VERNIER CALIPER 1.582

Figure 27-2-19 Practice is required for reliable reading of vernier scales.

The steps in reading a venier caliper are as follows:

1. Read the number of whole inches on the main scale that appear to the left of 0 on the venier.
2. Read the highest numbered graduation on the main scale that lies to the right of the index (0) on the vernier scale. Read these graduations as even one hundred *mil* (0.100, 0.200, etc.). Add to the whole inches from step one (1.100, 2.100, etc.).
3. Read the highest number of whole minor divisions to the right of the index. Read these graduations as even twenty-five *mil* (0.000, 0.025, 0.050, and 0.075 in.). Add to the sum of steps one and two (1.125, 1.150 in., etc.).
4. Now find the vernier graduation that most perfectly coincides with *any* graduation on the main scale. That is the nearest *mil* and may be any whole number from zero to 25 (0.000, 0.001, ... 0.024, 0.025). Add this to the sum of the previous three steps. It should be noted that only when the vernier is at zero will two lines, 0 and 25, for the vernier scale coincide with the main scale.

The principle is the same for metric verniers, as shown in Figure 27-2-20. Some modern instruments have both inch and metric scales. These provide the best of both worlds.

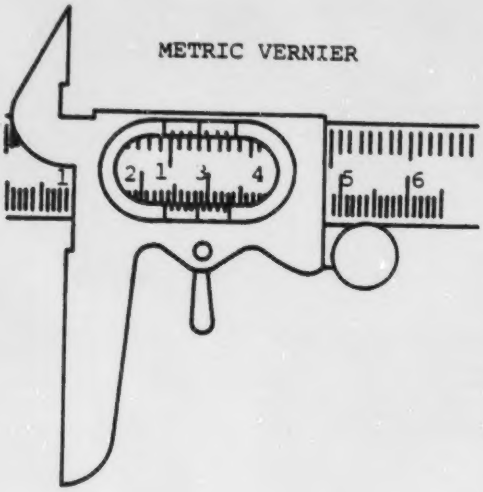


Figure 27-2-20 Nearly all vernier instruments are available with metric scales.

The advantages and disadvantages for vernier instruments are summarized in Table 27-2-2. Here is the essential point. Vernier scales are usually more reliable than the instruments on which they are used. It might be asked why the discrimination is limited? Could not the entire arrangement be expanded so that the discrimination to be reduced to, say, 0.0001 instead of 0.001 in.? A vernier designed to read to 0.0001 from an inch scale would have a group of lines so nearly in coincidence that they would be indistinguishable. Many modern vernier instruments do have expanded scales. The objective, however, is to achieve greater reliability by improved readability.

Table 27-2-2

ADVANTAGES AND DISADVANTAGES OF VERNIER SCALES

Advantages:

1. Amplification is achieved by design and is not dependent upon moving parts that may wear or go out of calibration.
2. No interpolation is possible in reading, let alone required.
3. There is no theoretical limit to the scale range (length).
4. Zero setting adjustment is easy.

Disadvantages:

1. The principal disadvantage lies in the instruments on which verniers are used.
2. The reliability of reading depends more upon the observer than most instruments.
3. The discrimination is limited.
4. No way to adjust for any errors other than zero setting.

An example of the vernier scale was shown in Figure 27-2-17(b). This modern 50-division vernier makes use of the amazing ability of the eye to bring lines into coincidence. It requires twice the visual acuity of a 25-division vernier, but is quite easy to use. Note that it does not increase the accuracy (that is mostly in the instrument construction), or the discrimination, but does increase the reliability.

In Figure 27-2-17(b) the beam graduations are shown to be in increments of 0.05 inch. The vernier has 50 graduations, each of which is equal to 0.05 ÷ 50 or 0.001 inch. Reading the vernier caliper of Figure 27-2-17(b) gives the following results:

Reading of Vernier Zero on Beam = 1.45 plus inches
Matching Graduation of Vernier with Beam = .014 inch
Composite Reading = 1.464 inches

Figure 27-2-21 shows this reading.

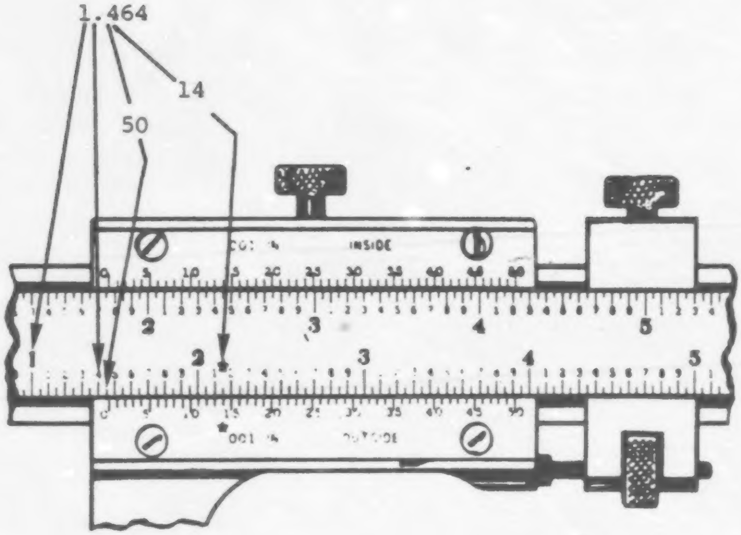

1.464
14
50
INSIDE
0 5 10 15 20 25 30 35 40 45 50
2
3
4
5
1
2
3
4
5
0 5 10 15 20 25 30 35 40 45 50
.001 IN
OUTSIDE

Figure 27-2-21 Reading a Vernier-50 Division

Description of Dial Caliper

Dial calipers are very similar to vernier calipers except that the vernier is replaced with a dial indicator. One revolution of the dial indicator is the equivalent of the vernier scale. Therefore, the reading of the dial indicator is added to the reading of the beam as shown in Figure 27-2-22.

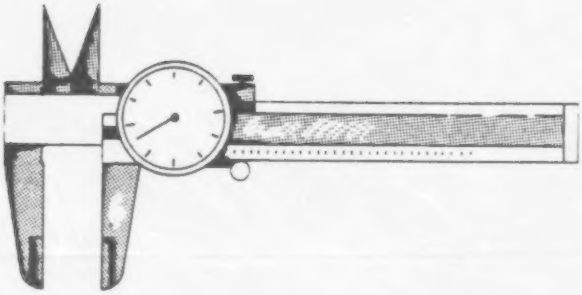


Figure 27-2-22 Dial Caliper

Applications of Vernier and Dial Calipers

Vernier and dial calipers are general purpose length measurement devices. Their sensitivity is 0.001 inch. Dial calipers give best accuracy of about 0.001 inch per 6 inch length of measurement. These devices provide for relatively fast measurements of lengths, diameters, widths, and heights. They are suitable devices for any of these features having a tolerance of 0.004 inch or more.

Sources of Error of Vernier and Dial Calipers

The manufacturing tolerances of the instruments establish the maximum possible accuracy and precision. Manufacturing tolerances are most critical for the width and surface finish of the contact portion of the jaws, the parallelism of the faces of the jaws, the perpendicularity of the faces of the jaws to the beam, the scale linearity, width of graduation lines, and the intervals of the dial indicator. Super smoother, knife edges of the jaws provide esentially a point contact with the boundaries of the dimension to be measured. This is particularly important when such boundaries have a radius. The dial indicator adds a new source of error referred to as hysteresis.

Hysteresis refers to a lagging of movement when direction of motion is changed. It affects both accuracy and precision.

Other sources of error are operator and procedure oriented. Positional consistencies and full and accurate reading of scale are important to operator techniques and precision. Standardization of calibration within a laboratory and from one organization to another is important.

MICROMETER

Description

Micrometers are specially designed calipers that work on the principle of a screw with a precisely controlled lead. A given rotation of the screw moves the spindle (movable jaw) a predictable distance such that accurate measurement is possible. The principal parts of a micrometer are shown in Figure 27-2-23.

The C-shaped frame should be used as the "handle" of this device. The spindle, thimble, and thimble sleeve are integrally connected to the lead screw (not visible in Figure 27-2-23). Turning the thimble sleeve turns the lead screw such that the span between the spindle and anvil becomes smaller or larger dependent on direction of rotation. The primary scale is on the barrel sleeve and is graduated in increments of 0.025 inch. The secondary scale is on the thimble, and is graduated in 25 increments with each increment equivalent to 0.001 inch movement along the sleeve scale. Some micrometers also have a vernier such as that shown in Figure 27-2-23. The vernier has ten graduations with each representing 0.0001 inch. The spindle lock serves to hold the spindle at the desired span when "locked". The friction nut is a ratchet device that helps

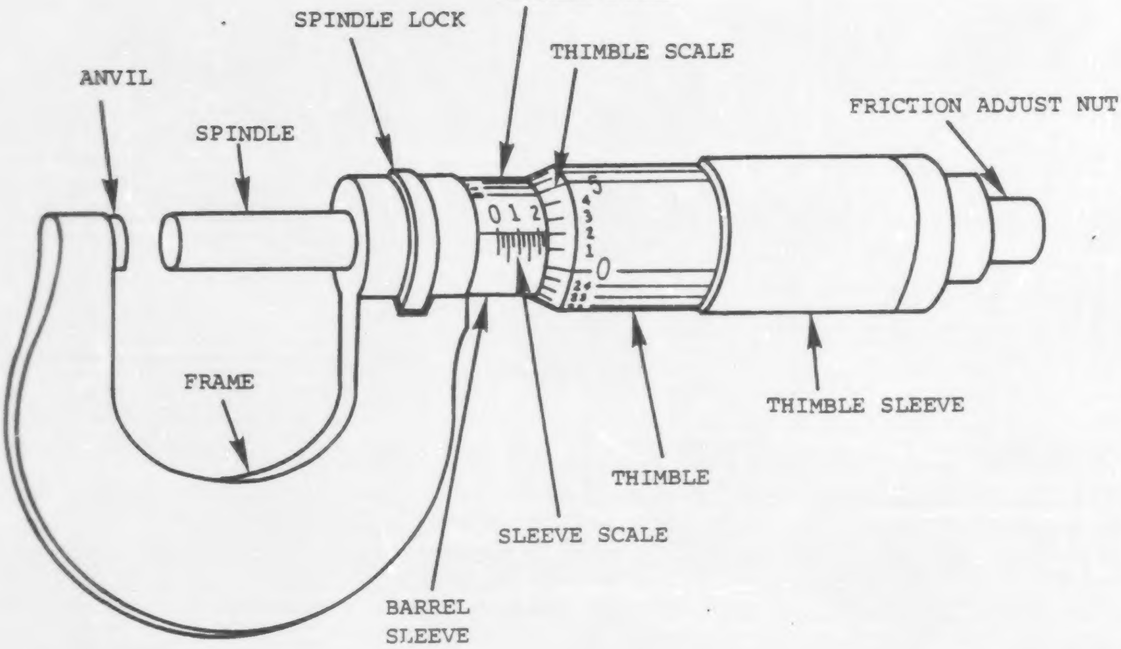

VERNIER SCALE
SPINDLE LOCK
THIMBLE SCALE
ANVIL
FRICTION ADJUST NUT
SPINDLE
0 1 2
5
4
3
2
1
0
FRAME
THIMBLE SLEEVE
THIMBLE
SLEEVE SCALE
BARREL
SLEEVE

Figure 27-2-23 Micrometer Nomenclature

to insure uniform pressure against the boundaries when measurements are made.

Micrometers are made in many sizes with either inch or millimeter units. They are designated by the maximum size that can be spanned by the frame. However, the spindle travel is normally only one inch for any size. For example, while a one inch micrometer measures from 0" to 1", a 2" micrometer spans two inches but still has one inch of spindle travel. Thus, the 2" micrometer measures from 1" to 2". Sets of micrometers are available in one inch increments up to a span of 18" with each having the usual one inch of spindle travel. Metric micrometers have equivalent ranges with the smallest from 0mm to 25mm and with larger spans up to 600mm. On larger micrometers, interchangeable anvil extensions are utilized to reduce the span in several increments for the sake of economy.

Micrometers have such improvements and special features as friction sleeves, ratches stops, spindle locks and slant line graduations as well as vernier scales that read to one/ten-thousandths (0.0001") of an inch. Probably the most dramatic mechanical change to occur in recent micrometer design is the advent of the direct reading digital micrometer. Digital micrometers can display a digital readout to 0.0001" in the U.S. System and 0.002mm in the S.I. System. The readout occurs in a non-revolving window built into the thimble of the micrometer.

Reading the Micrometer

The operation of a micrometer is based on an accurately machined screw, usually having 40 threads to the inch. With one complete revolution, such a screw will advance 1/40th or 0.025 of an inch. By putting graduations on the barrel sleeve which is fixed and on the thimble which moves with the screw, it is possible to determine the amount of movement of the screw, and thus to measure.

On inch reading micrometers, 40 graduations are placed on the barrel to match the number of threads on the screw such that each represent 0.025 inch of movement. To facilitate reading, every fourth line is numbered to show 0.100", 0.200" etc. to 1". (These correspond to the 0, 1 and 2 visible on the sleeve scale of Figure 27-2-23.)

The beveled edge of the thimble has 25 divisions around the circumference, numbered from 0 to 25. A beveled edge is used to reduce the parallax with the sleeve scale. When the micrometer is closed, only the zero line on the barrel can be seen next the beveled edge of the thimble, and the zero line on the thimble is aligned with the long axial line on the barrel, called the datum.

Every complete revolution of the thimble from 0° to 360° advances (or retracts) the spindle 1/40" ro 0.025" and moves the edge of the thimble from one graduation on the barrel to the next barrel graduation. With one graduation on the beveled edge of the thimble aligned with the datum on the barrel, rotation of the thimble to align the next thimble graduation with the datum moves the spindle a distance of 1/25th of 0.025" or 0.001". Because the thimble divisions, which represent 0.001" of movement of the screw, are widely spaced around the circumference of the thimble, 0.001" movement of the screw are easily seen and thus good readability is obtained.

To further increase the micrometer's capability to measure in even smaller increments than 0.001", many micrometers are made with a vernier scale on the barrel to divide thimble graduations of 0.001" into 10 parts, or 0.0001". The principle of the vernier, where 10 graduations on the barrel equal 9 graduations on the thimble, is identical with the principle employed in vernier calipers. When the thimble graduation does not lie exactly on the datum, the value of the vernier line that coincides with any graduation on the thimble is added to the reading. Thus, the reading of the micrometer in Figure 27-2-23 is 0.227 inch plus the value of the vernier which is not readable in the figure.

Metric reading micrometers are identical in principle. The differences are in the pitch of the screw, usually 50 threads per 25mm, and in barrel and thimble graduations to show 0.5mm for each revolution and 0.01 mm per thimble division. Vernier models discriminate to 0.002mm.

Types of Micrometers and Their Applications

- Outside Micrometers - The most common micrometer is the outside micrometer shown in Figure 27-2-23. It is used for measuring length dimensions where the spindle and anvil can be placed against the boundaries of the dimension. Most accurate measurement occurs when the two boundaries are parallel, flat surfaces. This permits the flats of the spindle and anvil to fit accuratley against the boundaries.
- Inside Micrometers - Inside micrometers are used for precision measurements of the diameters of holes and width of slots. With the use of supplementary measuring rods and spacing collars, holes from 1" to 12" diameters may be measured. This instrument is essentially the spindle and sleeve of a conventional micrometer and measuring rods of various lengths and diameters as shown in Figure 27-2-24. Various rod lengths permit measuring the the diameter of a hole at various depths.
- Disk or Lip Micrometer - This instrument is a conventional micrometer modified with disk-shaped anvil and spindle end. The extended "lips" of the spindle and anvil permit measurement of fin-like projections and other outside features where use of standard micrometer is obstructed as shown in Figure 27-2-25.
- Blade Micrometer - This modification of the conventional micrometer caliper has screw-driver shaped anvil and spindle end for measurements at the base of recesses, grooves, and other shallow depths of the outside dimension. The spindle is non-rotating as shown in Figure 27-2-26.

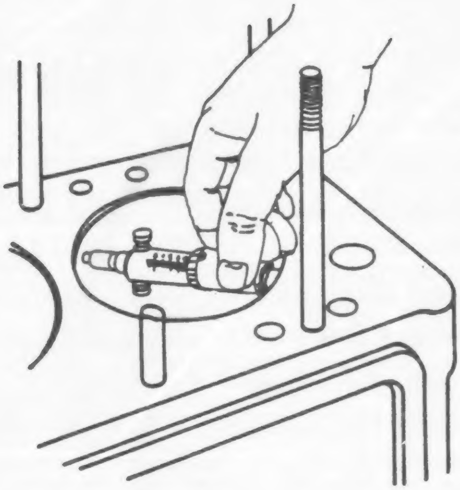


Figure 27-2-24 Using an inside micrometer to check cylinder bore size. (Austin-Healey)

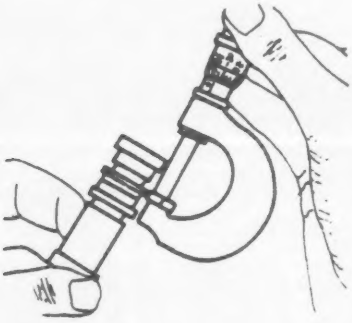


Figure 27-2-25 The Disc or Lip Micrometer

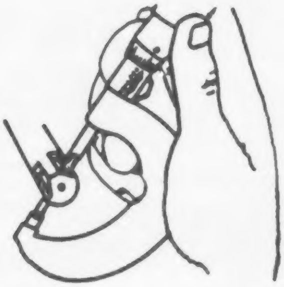


Figure 27-2-26 The Blade Micrometer

- Micrometer Depth Gage - In this instrument, interchangeable measuring rods of various lengths replace the conventional spindle and there is no anvil. The rod projects through an accurately finished base which provides a reference surface at right angles to the spindle. The rod travels as the thimble is turned, and depths up to 9" can be accurately measured as shown in Figure 27-2-27.
- Bore Measuring Micrometer (Intrimik) - This instrument permits direct measurement of hole size on a micrometer scale. It has three contact points traveling at right angles to the barrel, spaced 120° apart, which makes contact with the wall of the hole. With extension rods, readings accurate within a few ten-thousandths can be taken in holes up to 15" deep.
- Screw Thread Micrometer - This instrument is used for direct readings of the pitch diameters of screw threads. The vee-formed anvil and conical spindle tip are shaped to conform to the standard shape of the threads to be measured as shown in Figure 27-2-28.

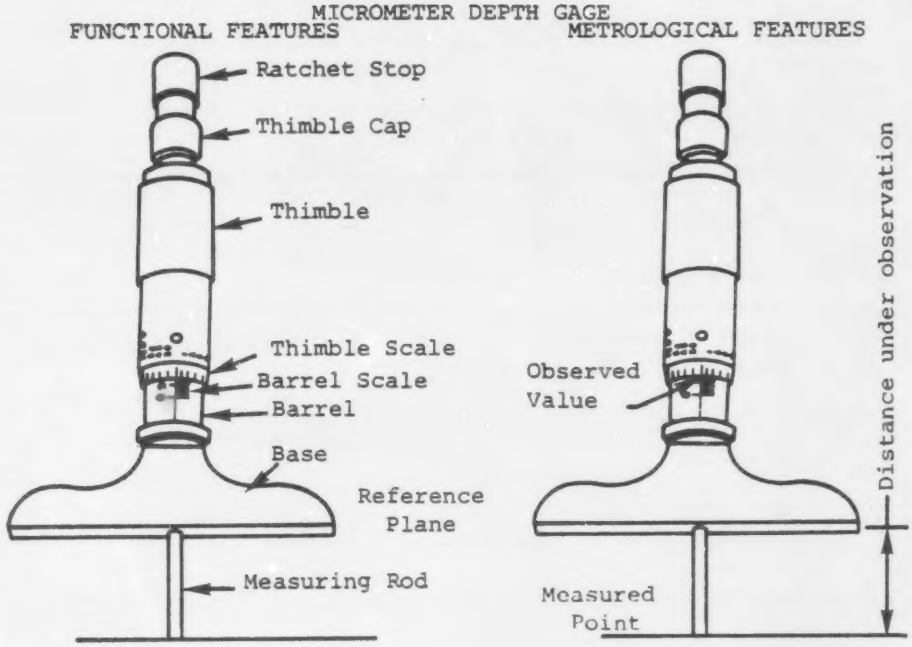

MICROMETER DEPTH GAGE
FUNCTIONAL FEATURES
METROLOGICAL FEATURES
Ratchet Stop
Thimble Cap
Thimble
Thimble Scale
Barrel Scale
Barrel
Base
Reference Plane
Measuring Rod
Observed Value
Distance under observation
Measured Point

Figure 27-2-27 The depth micrometer, unlike all other micrometers, measures from a plane to a point.

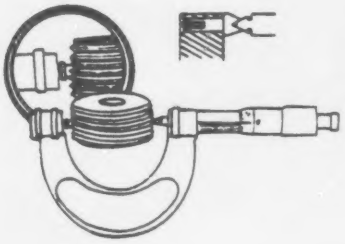


Figure 27-2-28 The Screw Thread Micrometer

- Pointed Contact Micrometer - This instrument uses conical anvil and spindle tips to measure recesses where flat tips could not reach.
- Bench Micrometer - Since the thimble graduations on a micrometer represent divisions of the smallest increment on the barrel, it is evident that enlargement of the circumference of the thimble will provide for wider spacing of the graduations and for additional finer divisions. A large thimble would be impractical on an instrument for hand use, but it is provided in the bench micrometer, which permits direct reading in 0.0001" and 0.002mm. The micrometer head is mounted on a rigid base, leaving both hands free for manipulation. Bench micrometers (sometimes called super mics) are used for outside dimensions where greater accuracy and precision are required.

Accuracy and Precision of Micrometers

Accuracy and precision of micrometers are generally better than the vernier caliper. Even with precise manufacture of these two types of instruments, the readability of the micrometer is better and the vernier of the micrometer increases sensitivity by a factor of 10.

Features of the micrometer that affect its accuracy and precision include the following:

- Spindle Thread Movement - The accuracy, linearity and stability of the thread directly affect accuracy and precision of measurements. The threads are precision ground during manufacture and hardened material is used that has good thermal stability. Wear of the threads during the life of the micrometer gradually reduces accuracy and precision. Wear in localized areas can also be considered as altering linearity.

- Flatness and Parallelism of Measuring Surfaces - Manufacturer of the micrometer holds very tight tolerances on flatness and parallelism of the measuring surfaces. Wear of these surfaces during use will degrade accuracy and precision.
- Deflection of the Frame - Deflection of the frame during measurements reduces accuracy and precision. Such deflection is eliminated by design of rigid frames and controlling the pressure applied across the measuring surfaces. Control of measuring pressure can be improved by use of ratchets or friction sleeves on the spindle movement.
- Use by the Operator - Inadequate alignment and reading errors are the most common operator induced errors. Reading errors are reduced by practice and more practice and by attentiveness during measurement. Alignment means finding the correct span. For small outside micrometers, the best "feel" is normally by manipulation of the micrometer with one hand as shown in Figure 27-2-29. For large outside micrometers, the weight of the micrometer is supported by one hand on the frame while the spindle is adjusted with the other hand. For inside dimensions, the maximum span is sought. This occurs when the measuring surfaces are at right angles to the face of the bore. For either outside or inside measurements, the operator should select the type of micrometer that best measures the feature (See previous discussion on types of mircometers and their applications).

1. Adjust span to slightly larger than dimension to be measured.
2. Hold the micrometer with the little and ring fingers around the frame.

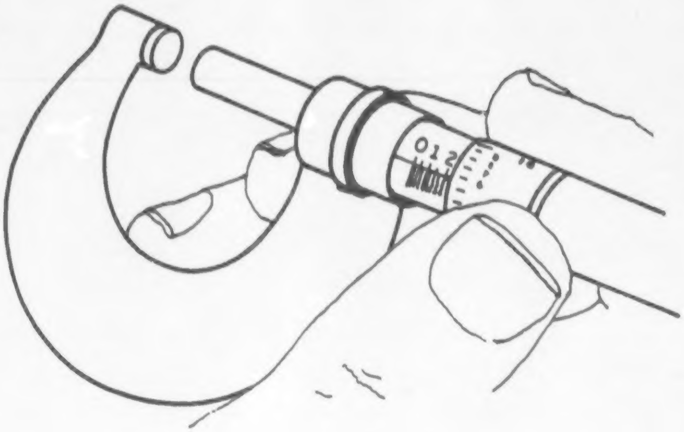


Figure 27-2-29 Manipulation of Small Micrometer

3. Place micrometer span across feature to be measured.
4. Close span by turning the thimble and forefinger.

Reading the Micrometer

Micrometers are made so that every turn of the thimble will move the spindle .025 in. You will notice that the sleeve is marked with a series of lines. Each of these lines represents .025. Every fourth one of these .025 markings is marked 1, 2, 3, 4, 5, 6, 7, 8, 9. These numbers on the sleeve indicate .001, .200, .300, etc., (one hundred thousandths etc.) markings. They will read from .000 to 1.000.

The tapered end of the thimble has twenty-five lines marked around it. They read 0, 5, 10, 15 and 20. In that one turn of the thimble moves the thimble edge exactly .025, or one mark on the sleeve, the distance between marks is determined by reading the thimble line that is even with the long line drawn the length of the sleeve markings.

Look at the markings on the micrometer in Figure 27-2-30 there are three numbers visible on the sleeve? The 3 indicates that the mike is open at least .300 (three hundred thousandths). The thimble edge is actually past the 3 but not to the 4. By a careful study you will see that the thimble edge has moved exactly two additional marks past the 3. This means that the edge is lined up two marks past the 3. As each mark represents .025, it is obvious that the edge is actually stopped at .300 plus .050 or .350 (three hundred and fifty thousandths of an inch). In that the thimble edge 0 marking is in line with the line through the sleeve markings, the micrometer is set exactly on .350. The reading then, if this were a one inch mike (reads from 0-1 inch), would be .350.

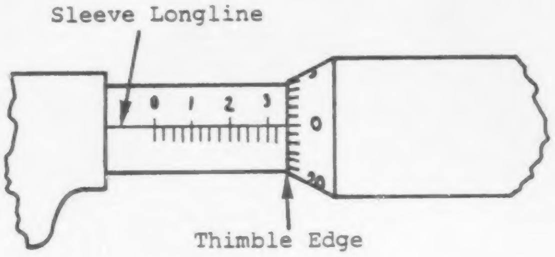


Figure 27-2-30 Micrometer reads - 0.350

In Figure 27-2-31, the micrometer has been opened to a wider measurement. You will see that the thimble edge is no longer exactly on a sleeve marking but is somewhere in between.

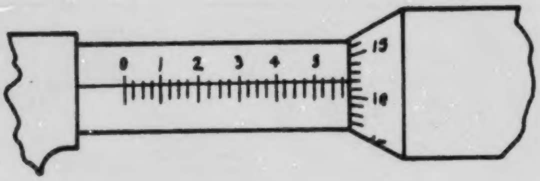


Figure 27-2-31 Micrometer reads - 0.587

How many numbers are visible on the sleeve? There are 5 or .500 (five hundred thousandths). The thimble edge has moved three marks or .075 past the .500 mark. This makes a total of .575. The thimble edge has moved past the third mark. In that the fourth mark is not visible, we know that it is somewhere between the third and fourth mark.

By examining the thimble edge marks, one will see that the twelfth mark is aligned with the sleeve long line. This means that the thimble edge has moved twelve spindle marks past the third sleeve mark. In that each thimble mark is worth .001 (one thousandth of an inch), the thimble has actually moved .012 (twelve thousandths of an inch) past the third sleeve mark. Your reading then would be .500 (largest sleeve number visible) PLUS .075 (three sleeve marks past sleeve number) PLUS .012 (twelve thimble marks past the third sleeve mark), making a total reading of 0.587 (five hundred and eighty-seven thousandths of an inch).

Study the readings shown in Figure 27-2-32. Compare your answers with those shown. Make your reading in FOUR steps.

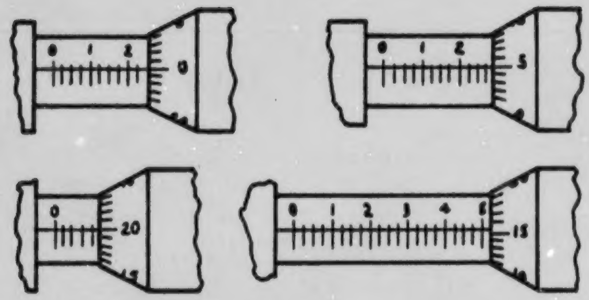


Figure 27-2-32 Reading the "mike". A-0.250. B-0.280. C-0.120. D-0.515-1/2, or 0.5155.

1. Read the largest sleeve number that is visible - each one is worth .100.
2. Count the number of full sleeve marks past this number. Each one is worth .025.
3. Count the number of thimble marks past this last sleeve number. Each one is worth .001. If the thimble marks are not quite in line with the sleeve line, estimate the fraction of a mark.
4. Add the readings in steps 1,2 and 3.
   The total is the correct micrometer reading.

EXERCISES

Perform the following exercises employing the procedures which are outlined in a following section in this module.

1. Measure an unknown length with a divider.
2. Transfer a standard length to a workpiece with a divider.
3. Perform a GO-NO GO measurement with a outside calipers.
4. Perform a measurement using an inside caliper.
5. Discuss the factors affecting accuracy and precision of dividers and calipers in relationship to the procedures used in making measurements with these instruments.
6. Perform the practice exercises given in the Procedures section of this module.
7. Perform inside and outside measurements using vernier or dial calipers.
8. Perform the micrometer reading exercise outlined in the Procedures section of this module. Using an outside micrometer perform outside measurements on tubing and wire.
9. Using an inside micrometer perform inside measurements on a cylinder bore.
10. Perform cylindrical plug and ring measurements to demonstrate the use of GO-NOT GO cylindrical plug and ring gages.

MATERIALS

The following materials are suggested to support this module:

1. Steel plate machined by a nearby machine shop to have a series of holes and counter bores of nominal diameters equal to available plug gages.
2. Flanges with drilled bolt holes from nearby industries.
3. Machined shafts such as dowel pins, axles, valve stems, plug shafts, motor shafts,
4. Steel plate machined by a nearby machine shop to have threaded holes of designated sizes.
5. Flange with threaded holes.
6. Parts with threaded holes such as valve bodies and pump casings.
7. Threaded screws of the Unified System.
8. Threaded studs of the Unified System.
9. Shafts with external threads of the Unified System.
10. Steel rules or scales.
11. Dividers.
12. Calipers.
13. Vernier and Dial Calipers.
14. Micrometers.
    a. outside
    b. inside
    c. depth
    d. other (thread, disc, etc.)
15. Fixed gages.
    a. Cylindrical ring and plug gages.
    b. Threaded ring and plug gages.
16. Parts for measurement.
    a. Vee blocks.
    b. Others (drilled plate, flanges, pump parts, valve parts, etc.)

PROCEDURES

A. Procedures on the use of Dividers and Calipers

Dividers and calipers can transfer a known length from the standard to the workpiece and can transfer an unknown length from the workpiece to the standard. The following procedures allow the students/trainees to demonstrate these uses.

1. Measurement of an unknown with a divider.

   Exercises: What is the distance between lines of lined notebook paper?

   Procedure:

   a. Loosen thumb nuts to permit adjustment of the span of the dividers.
   b. Place one tip on any line of the notebook paper.
   c. Adjust span until the other tip is on an adjacent line at maximum arc radius.
   d. Tighten thumb nuts without changing the desired span.
   e. Place one tip at a unit interval of a steel scale and read the length of scale to the other tip.
   f. Repeat the above steps for other sets of lines on the notebook paper and average the results.

2. Transfer of Standard Length of a Workpiece with a divider.

   Exercise: Draw a line parallel to and four inches to the right of the left hand margin line of lined notebook paper.

   Procedure:

   a. Loosen the thumb nuts to permit adjustment of the span of the divider.
   b. Place one tip on a unit of a steel rule graduated in inches.

c. Adjust span until the other tip is on the fourth unit from the first tip.

d. Tighten thumb nuts without changing the desired span.

e. Place one tip on left hand margin line of notebook paper in the upper portion of the paper.

f. With the other tip lightly scratch an arc at a right angle and to the right of the margin line.

g. Repeat the above two steps but in the lower portion of the paper.

h. Using a straight edge, draw a line tangent to the extreme right points of the arcs.

i. Describe why the arcs were used in this solution rather than placing the divider of desired span at the intersection of the margin and any line and at the set span along the same line. (HINT: What geometrical relationship would have to exist between the margin line and the space lines?)

3. Go-No Go Measurement with Outside Calipers

Given: Cylindrical part whose outside diameter must be x as a minimum and y as a maximum. (Examples of parts that may be selected include pipe, cylindrical bar stock, tubing, conduit, cylindrical standards.)

Exercise: Is the part within tolerance?

Procedure:

a. Select two outside calipers whose span is compatible with the outside diameter limits.

b. Set on caliper to a steel rule to a span equal to x.

c. Set the other caliper to a steel rule to a span equal to y.

CAUTION: In the next step, do not force the caliper onto the outside diameter such that the span setting is altered.

d. Measurement outside diameter of the cylinder at various locations with the caliper set at x and check one of the following:
    (1) The caliper will not span the diameter at any location.
    (2) The caliper will span the diameter at least one location.
    (3) Measure the outside of the cylinder at various locations with the caliper set at y and check one of the following:
    (4) The caliper will not span the diameter at any location.
    (5) The caliper will span the diameter of at least one location.

e. Determine if the part is within tolerance from the conclusion that the x value caliper should not span an in tolerance diameter and the y value caliper should span an in tolerance diameter.

f. Check the transfer method used in this exercise:
    (1) Standard transfer to workpiece.
    (2) Unknown transfer to standard.

4. Measurement with Inside Caliper

   Given: Hollow cylindrical part or drilled hole of unknown inner diameter.

   Exercise: What is the value of the inner diameter?

   Procedure:

   a. Loosen thumb nuts of inside caliper to permit adjustment of span.
   b. Place tips of caliper inside the inner diameter.
   c. Adjust span of inside caliper until the tips are against diametrically opposite walls at the largest possible span. (NOTE: The student/ trainee should be alert for the "feel" of the caliper. As one tip is held and the second tip is moved along the arc of the opposite wall, a shortening and lengthening of the span is noted. The most accurate measurement occurs with the longest span of the caliper.)
   d. With the longest possible span, tighten the thumb nuts.
   e. Place one tip of the caliper on a unit of a steel rule and read the distance of the scale from that point to the point where the other tip lies.

5. Factors Affecting the Accuracy and Precision of Dividers and Calipers

   Student/trainees should relate their experiences from the above exercises to the following discussion.

   a. Accuracy. Accuracy is dependent on the accuracy of the standard. If the steel rule is used as the standard, the maximum possible accuracy is that of the steel rule. Factors affecting accuracy are primarily:

(1) Alignment of divider/caliper tips with the standard.

(2) Position of the divider/caliper relative to the standard or the workpiece. Tipping, canting, or cocking introduces error.

(3) Pressure of tips against the standard or workpiece. The "feel" is involved.

(4) Skill of the operator. Again, feel is involved as well as skills in manipulation and adjustment of thumb nuts.

(5) Cleanliness of the workpiece and instrument.

(6) Lighting level. The lighting level should offer easy readability.

b. Precision. Precision is primarily dependent on the operator. It is affected by all the sources of error discussed under accuracy.

c. Sensitivity. The sensitivity can equal that of the standard at best. It is affected by the "feel" of the divider/caliper and the discrimination of the standard.

d. Readability. Readability is that of the standard.

e. Linearity. Linearity is that of the standard except that different "feel" at different spans will affect linearity.

B. Procedures on the use of Vernier and Dial Calipers

Students/trainees should practice making measurements with vernier and dial calipers on objects supplied by the instructor. Suitable objects include veeblocks, pipe, bar stock, surplus parts, tubing. The following guidance is provided.

1. Prior to making measurements, practice loosening the set screws, moving the slide with the fine adjust, and tightening the set screws until a comfortable "feel" of the instrument is obtained.

2. To make outside measurements:
   a. Open the jaws to easily span the dimension.
   b. Hold the stationary jaw with one hand against one boundary of the dimension.
   c. With the other hand, move the slide until the movable jaw contacts the other boundary.
   d. Very lightly rock and yaw the beam while at the same time adjusting the fine adjust such that a light pressure contact is made by the jaws with both boundaries. Notice the "feel" of the device. Note that the minimum span is the most accurate measurement of the outside dimension. Note that as the minimum span is approached, the device feels rigid against the workpiece.
   e. At the minimum span, either read the measurement or tighten the set screws and carefully remove the device for reading.

3. To make inside measurements:
   a. Close the jaws to easily enter the inside dimension.
   b. Hold end of beam opposite the jaws with one hand and move the slide with the other hand until the jaws contact both boundaries.
   c. Adjust the fine adjust while very slightly rocking and yawing the beam with the other hand until a light pressure contact is made

by both jaws with the boundaries. Note that the maximum span is the most accurate measurement of the inner dimensions. Note that as the maximum span is the most accurate measurement of the inner dimensions. Note that as the maximum span is approached, the device feels rigid against the workpiece.

   d. At the maximum span, either read the measurement or tighten the set screws and carefully remove the device for reading.

4. Practice in reading the vernier:
   a. Read the verniers pictured in Figure 27-2-33 to develop skill in reading vernier calipers.
   b. Check answers with the answer key sheet given on the subsequent page.

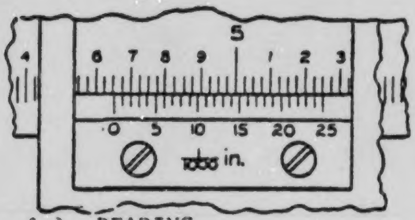
5. Repeat the vernier reading exercise with actual vernier calipers.

C. Procedures on the use of Micrometers

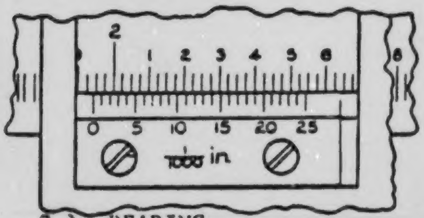
1. The principle of micrometer measurements is that a given rotation of a precision screw will move the spindle a predictable distance.

2. One complete revolution of the micrometer thimble moves the spindle one graduation on the barrel; therefore, the graduations on the thimble divide one barrel graduation into equal parts.

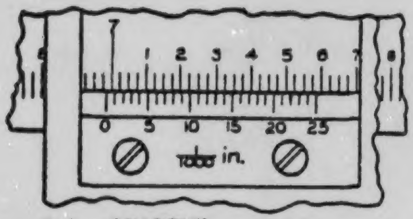
3. Micrometers without verniers have discrimination of 0.001 inch while those with verniers have discrimination of 0.0001 inch.


4
6 7 8 9 5 1 2 3
0 5 10 15 20 25
1/1000 in.

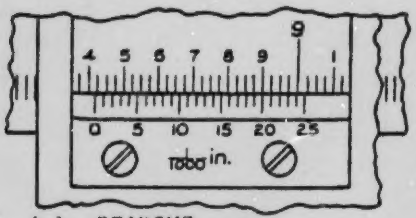
1.) READING ______


2
1 2 3 4 5 6
8
0 5 10 15 20 25
1/1000 in.

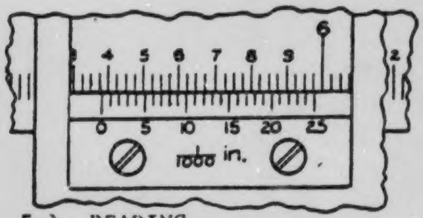
2.) READING ______


7 1 2 3 4 5 6 7
8
0 5 10 15 20 25
1/1000 in.

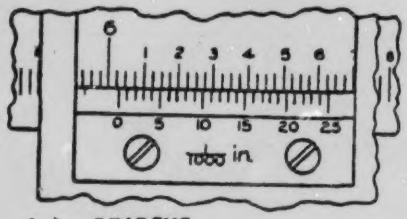
3.) READING ______


4 5 6 7 8 9 9 1
0 5 10 15 20 25
1/1000 in.

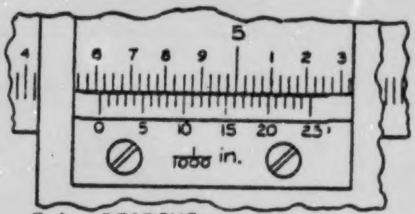
4.) READING ______


4 5 6 7 8 9 6
2
0 5 10 15 20 25
1/1000 in.

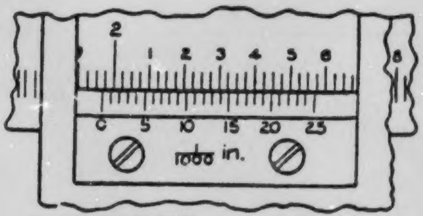
5.) READING ______


6 1 2 3 4 5 6
8
0 5 10 15 20 25
1/1000 in.

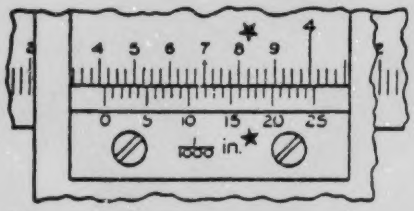
6.) READING ______


4
6 7 8 9 5 1 2 3
0 5 10 15 20 25
1/1000 in.

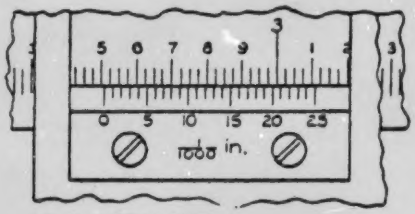
7.) READING ______


2
1 2 3 4 5 6
8
0 5 10 15 20 25
1/1000 in.

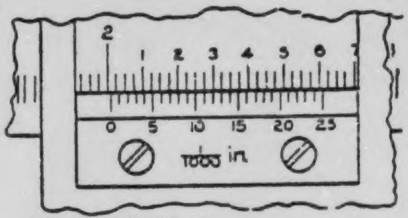
8.) READING ______


4 5 6 7 8 9 4
2
0 5 10 15 20 25
1/1000 in.

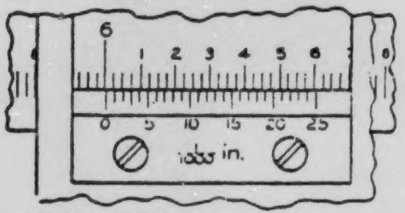
9.) READING ______


5 6 7 8 9 3 1 2
3
0 5 10 15 20 25
1/1000 in.

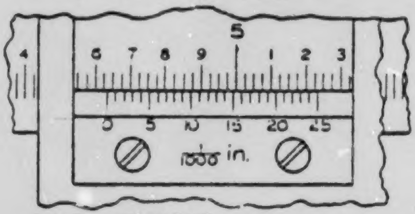
10.) READING ______


2
1 2 3 4 5 6 7
0 5 10 15 20 25
1/1000 in.

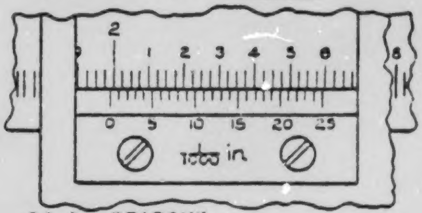
11.) READING ______


6 1 2 3 4 5 6
8
0 5 10 15 20 25
1/1000 in.

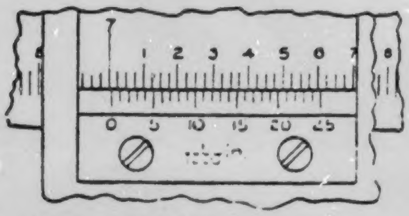
12.) READING ______


4
6 7 8 9 5 1 2 3
0 5 10 15 20 25
1/1000 in.

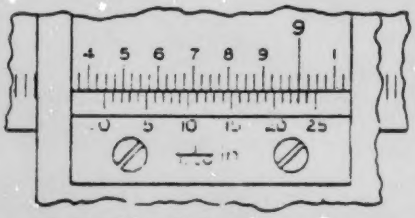
13.) READING ______


2
1 2 3 4 5 6
8
0 5 10 15 20 25
1/1000 in.

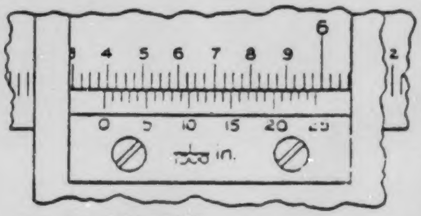
14.) READING ______


7 1 2 3 4 5 6 7
8
0 5 10 15 20 25
1/1000 in.

15.) READING ______


4 5 6 7 8 9 9 1
0 5 10 15 20 25
1/1000 in.

16.) READING ______


4 5 6 7 8 9 6
2
0 5 10 15 20 25
1/1000 in.

17.) READING ______

Figure 27-2-33 Vernier Reading Exercise

Answers to the Vernier Reading Exercises:

Student/trainee answers should be within ± 0.001 inch.

1. 4.652 inches
2. 1.945 inches
3. 6.987 inches
4. 8.421 inches
5. 5.383 inches
6. 6.028 inches
7. 4.612 inches
8. 1.968 inches
9. 3.417 inches
10. 2.508 inches
11. 2.011 inches
12. 6.003 inches
13. 4.633 inches
14. 1.993 inches
15. 7.010 inches
16. 8.448 inches
17. 5.338 inches

4. Many designs of micrometers are available; examples of micrometers and their applications are:

Type	Application
Outside	lengths, widths, heights, outside diameters
Inside	inside diameter, slot width
Disk	width of fins or fin-like projections
Blade	outside dimensions of grooves or recesses
Depth	depth of counter bores, non through holes
Bore (Intrimik)	holes diameters
Screw Thread	pitch diameters
Pointed Contact	dimension of recesses
Bench	outside dimension requiring great accuracy

5. Factors affecting accuracy and precision of measurements with micrometers include:
   a. spindle thread movement's accuracy, linearity, and stability
   b. flatness and parallelism of measuring surfaces
   c. deflection of frame
   d. operator alignment and contact pressure of instrument and skill in

6. Micrometer Reading Exercises
   a. Read the micrometer scales pictured on Figure 27-2-34.
   b. Check your answers with the answer key provided.

7. Repeat the micrometer reading exercise with actual micrometers.

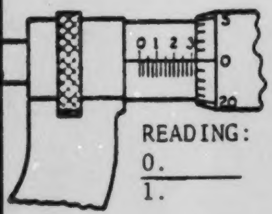
8. Using the micrometer, perform outside measurements on tubing and wire.

9. Using an inside micrometer perform inside measurements on a cylinder bore.

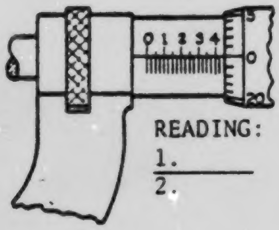
D. Procedures on the use of Cylindrical Plug and Ring Gages and Thread Plug and Ring Gages

Students/trainees should be given assignments to make measurements with at least cylindrical plug and ring gages and thread plug and ring gages. If other types of fixed limit gages are available, assignments are recommended for students/trainees to make measurements with fixed cylindrical and thread gages. Alternate procedures may be used.

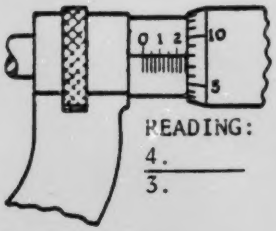
Read the scale of micrometers shown on this page. Try to read each scale to the nearest 0.001 inch. Check answers with the answer key.



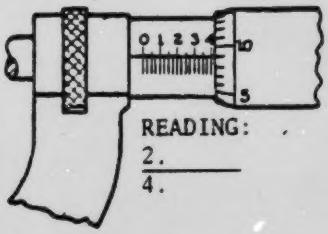
READING:
0.
1.



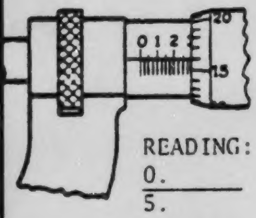
READING:
1.
2.



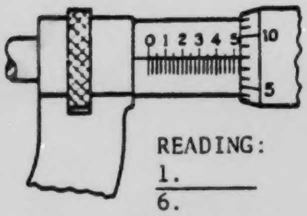
READING:
4.
3.



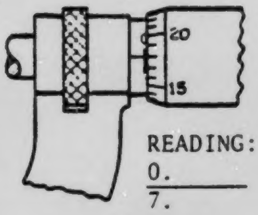
READING:
2.
4.



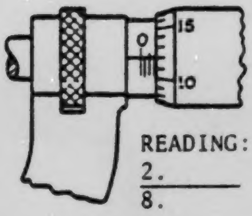
READING:
0.
5.



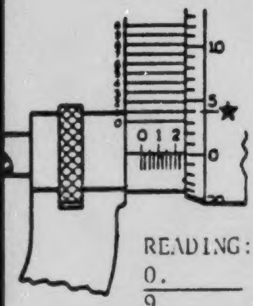
READING:
1.
6.



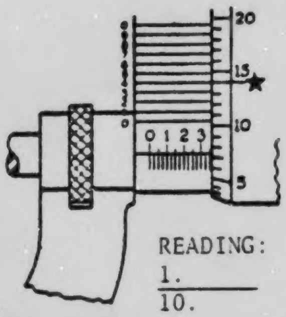
READING:
0.
7.



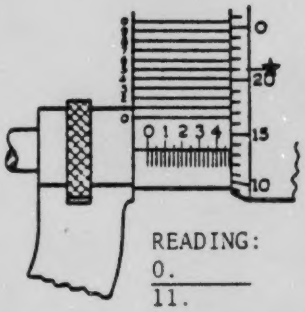
READING:
2.
8.



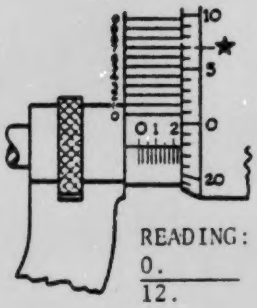
READING:
0.
9.


0 1 2 3
20
15
10
5

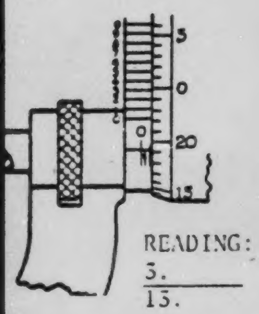
READING:
1.
10.


0 1 2 3 4
0
20
15
10

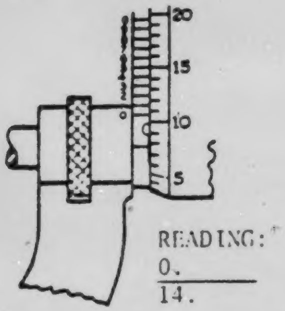
READING:
0.
11.



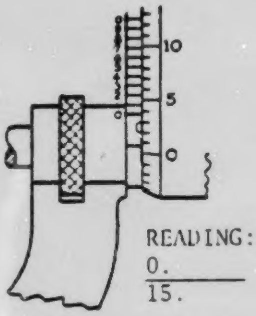
READING:
0.
12.



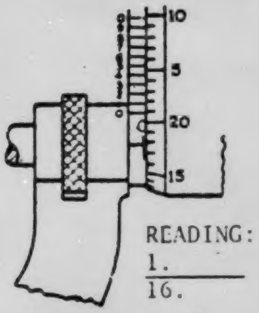
READING:
3.
13.



READING:
0.
14.

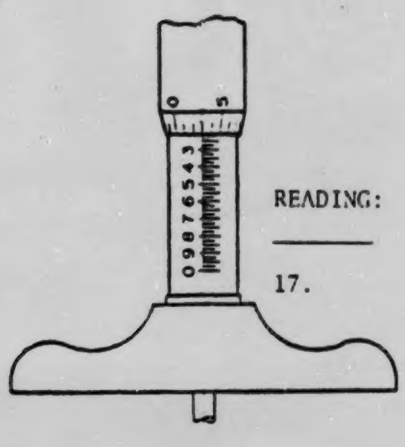


READING:
0.
15.



READING:
1.
16.

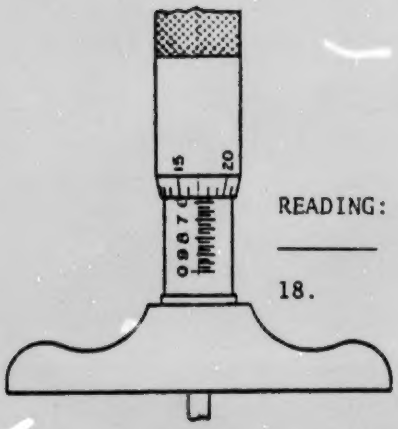
Figure 27-2-34 Micrometer Reading Exercise
(Page 1 of 2)


0
5
09876543

READING:

______

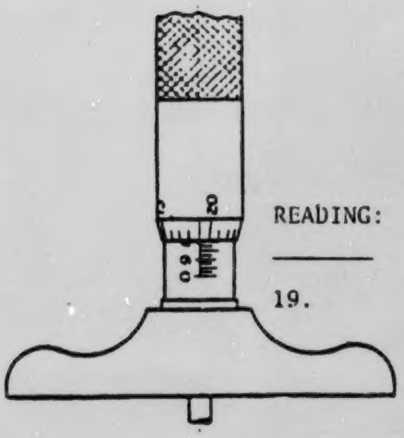
17.



READING:

______

18.



READING:

______

19.

Figure 27-2-34 Micrometer Reading Exercise
(Page 2 of 2)

Answers to Micrometer Reading Exercise

1. 0.325 inch
2. 1.450 inches
3. 4.258 inches
4. 2.409 inches
5. 0.291 inche
6. 1.533 inches
7. 0.018 inch
8. 2.062 inches
9. 0.2501 inch
10. 1.3574 inches
11. 0.4635 inch
12. 0.2477 inch
13. 3.0442 inches
14. 0.0075 inch
15. 0.0006 inch
16. 1.0178 inches
17. 0.228 inch
18. 0.567 inch
19. 0.794 inch

1. Perform Cylindrical Plug Measurements
   Suggested parts for measurement:
   ___ Steel plate machined by a nearby machine shop to have a series of holes and counter bores of nominal diameters equal to available plug gages.
   ___ Flanges with drilled bolt holes from nearby industries.
   a. Using tolerances of the holes provided by the instructor, select the proper GO and NOT GO cylindrical plug gage.
   b. Clean the holes and the plug.

c. Prepare a sketch picturing the layout of the holes with respect to the part features. If the holes are not numbered, assign arbitrary numbers for identification purposes.
d. Measure each hole by determining that the GO gage enters fully and the NOT GO gage does not enter or otherwise indicate the condition that exists.
e. Record on the sketch the acceptance or rejection of each hole.

2. Perform Cylindrical Ring Measurements
Suggested parts for measurement: Machined shafts such as dowel pins, axles, valve stems, pump shafts, etc.
    a. Using tolerances of the parts provided by the instructor, select the proper GO and NOT GO cylindrical ring gage.
    b. Clean the parts and the gages.
    c. Prepare a table consisting of these columns: (a) part number, (b) part tolerance, (c) value of GO gage, (d) value of NOT GO gage, (e) part accepted, (f) part rejected. If the parts are unnumbered, assign arbitrary numbers for identification purposes.
    d. Measure each part by determining whether the part accepts the GO gage for its full length and does or does not accept the NOT GO gage.
    e. Record in column (e) or (f) of the table prepared in step 4 whether the part is accepted or rejected.

3. Perform Thread Plug Measurements

Suggested parts for measurement:

___ Steel plate machined by a nearby machine shop to have threaded holes of designated sizes.

___ Flange with threaded holes.

___ Parts with threaded holes such as valve bodies and pump casings.

a. Using the thread designations provided by the instructor, select the proper GO and HI thread plug gage.

b. Clean the threaded holes and the threaded gages. (NOTE: Bottom tapped holes may cause trapped air to seize plug gages which do not have a chip groove.)

c. Prepare a sketch showing the layout of the threaded holes with respect to the part features. Show hole serial numbers or assign arbitrary identification numbers for correlation.

d. Measure each threaded hole by determining whether the GO thread gage enters entire length of the threads and the HI gage does or does not present a definite drag on or before three turns.

e. Record on the sketch whether each hole is acceptable or rejected.

4. Perform Thread Ring Measurements

Suggested parts for measurement:

___ Threaded screws for the Unified System

___ Threaded studs of the Unified System

___ Shafts with external threads of the Unified System

a. Using the thread designation provided by the instructor, select the proper thread ring gages.
b. Clean the parts and the gages.
c. If the thread ring gages are adjustable, set the GO and LO gages with a master thread plug gage provided by the instructor.
d. Prepare a table having these columns: (a) serial number of part, (b) thread designation, (c) GO thread gage identification, (d) LO thread gage identification, (e) part accepted and (f) part rejected.
e. Measure the threaded parts by determining whether the GO thread gage engages the entire length of thread and the LO thread gage presents a definite drag on or before three turns.
f. Record in column (e) or (f) of the table whether the parts is accepted or rejected.

5. Perform a comparison among rules, calipers, vernier calipers and micrometers by measuring the same dimension with each and comparing results.
   a. Select a vee-block and measure its width with each of the following instruments; record results in the accompanying Data Table.
      - steel rule
      - outside caliper with the steel rule as the standard
      - vernier caliper
      - outside micrometer
   b. If the steel rule is graduated in fractions, convert the measurements of the rule and caliper to a decimal and record on the accompanying

116

Data Table. (See conversion table appended to this procedure.)

c. Obtain from the instructor the true value of the width of the vee-block.

d. Determine the relative accuracy and discrimination of the four instruments and place numerical ranking values in columns (2) and (5) of the Data Table where 1 is most accurate or has best discrimination and 4 is least.

e. Compare your measured values with those of another student/trainee in column (4) of the Data Table, state your opinion of the rationale of any differences in measured values. If you both have identical values, state "same" in column (4).

DATA TABLE

MEASUREMENT OF VEE BLOCK WIDTH				
	MEASURED VALUE (1)	RELATIVE RANKING		COMPARISON WITH ANOTHER STUDENT/TRAINEE MEASURED VALUES; RATIONALE FOR DIFFERENCES (4)
		ACCURACY (2)	DISCRIMINATION (3)	
Steel Rule				
Outside Caliper				
Vernier Caliper				
Micrometer				
True Value Provided by Instructor				

This conversion table is provided for the convenience of the student/trainee for any laboratory work requiring conversion of decimals to fractions and vice-versa.

DECIMAL EQUIVALENTS

1/64	.015625
1/32	.03125
3/64	.046875
1/16	.0625
5/64	.078125
3/32	.09375
7/64	.109375
1/8	.125
9/64	.140625
5/32	.15625
11/64	.171875
3/16	.1875
13/64	.203125
7/32	.21875
15/64	.234375
1/4	.25
17/64	.265625
9/32	.28125
19/64	.296875
5/16	.3125
21/64	.328125
11/32	.34375
23/64	.359375
3/8	.375
25/64	.390625
13/32	.40625
27/64	.421875
7/16	.4375
29/64	.453125
15/32	.46875
31/64	.484375
1/2	.5
33/64	.515625
17/32	.53125
35/64	.546875
9/16	.5625
37/64	.578125
19/32	.59375
39/64	.609375
5/8	.625
41/64	.640625
21/32	.65625
43/64	.671875
11/16	.6875
45/64	.703125
23/32	.71875
47/64	.734375
3/4	.75
49/64	.765625
25/32	.78125
51/64	.796875
13/16	.8125
53/64	.828125
27/32	.84375
55/64	.859375
7/8	.875
57/64	.890625
29/32	.90625
59/64	.921875
15/16	.9375
61/64	.953125
31/32	.96875
63/64	.984375
1	1.

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ANSI B1.1, Unified Inch Screw Threads, American National Standards Institute, New York New York.

TEST

Read each question carefully. Be sure to provide the specific information each question requires. Make your answers brief. Use the backs of the test if you need more space.

1. Define GO GAGE. ____________________

2. Define NOT GO GAGE. ____________________

3. Name one typical use of each of the following gages:
   a. cylindrical plug gage ____________________
   b. cylindrical ring gage ____________________
   c. thread plug gage ____________________
   d. limit snap gage ____________________

4. Name three error sources common to all fixed limit gages.

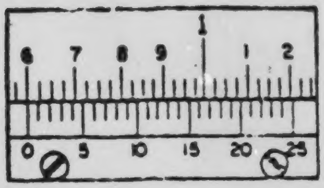
5. Describe the difference between a master fixed gage and a limit fixed gage.

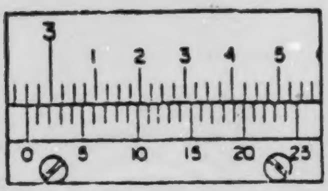
6. In the thread designation .250-20 UNF-1B, what is represented by each of the following:
   a. .250 ______
   b. 20 ______
   c. F ______
   d. B ______

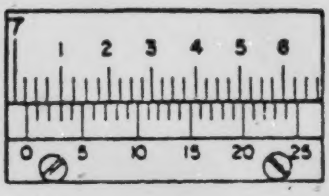
7. Name one typical use of each of the following:
   a. slide caliper ______
   b. vernier caliper ______
   c. outside micrometer ______
   d. inside micrometer ______

8. Name three error sources associated with the major vernier caliper.

9. Give the reading of the following vernier scales:


6 7 8 9 1 1 2
0 5 10 15 20 25


3 1 2 3 4 5
0 5 10 15 20 25


7 1 2 3 4 5 6
0 5 10 15 20 25

a. Reading_________ b. Reading________ c. Reading________

10. Name three error sources associated with the outside micrometer.

____

____

____

____

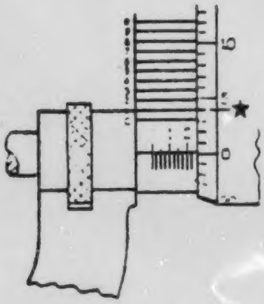
____

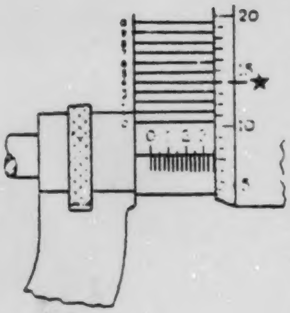
____

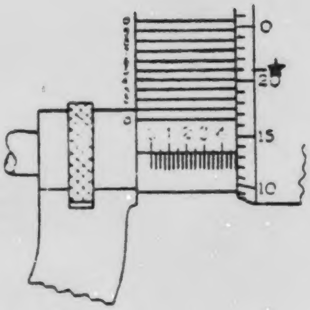
____

____

11. Give the reading of the following micrometer scales:







a. Reading________ b. Reading________ c. Reading________

12. Describe how to measure an outside length dimension with a vernier caliper by listing five steps in proper sequence for making the measurement.

a. ______________________________

b. ______________________________

c. ______________________________

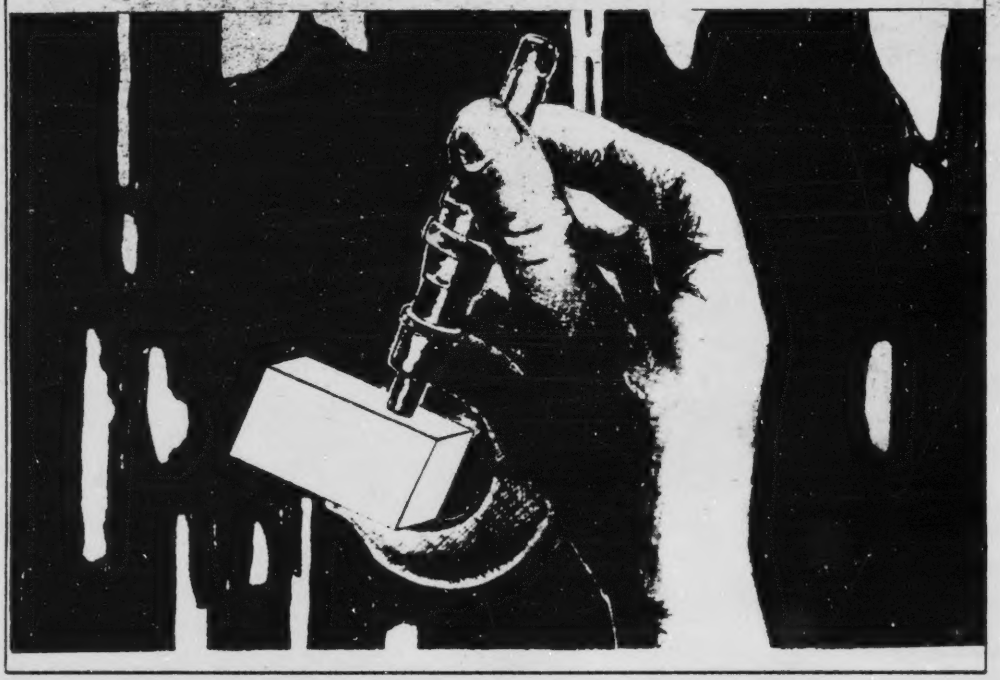
d. ______________________________

e. ______________________________

NUCLEAR TECHNOLOGY

MODULE 27 - 3

GAGE BLOCKS, MECHANICAL COMPARATORS AND ELECTRONIC COMPARATORS



COURSE 27: METROLOGY

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 27 METROLOGY

MODULE 27-1	Fundamentals of Metrology
MODULE 27-2	Fixed Gages, Dividers, Calipers and Micrometers
⇨ MODULE 27-3	Gage Blocks, Mechanical Comparators and Electronic Comparators
MODULE 27-4	Angle Measurement Instruments, Optical Projectors and Surface Texture Gages
MODULE 27-5	Tolerancing
MODULE 27-6	Calibration
MODULE 27-7	Statistical Techniques in Metrology
MODULE 27-8	The Total Measurement System

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INTRODUCTION

Many different types of measuring devices are available for use in dimensional inspection. The primary factors involved in selection of the "best" device are the type of dimension to be measured, the tolerance of the dimension and the characteristics of the measuring device. Modules 27-2, 27-3 and 27-4, describe various types of measuring devices, their typical applications and sources of errors in measurements with each type. Module 27-5 describes tolerancing methods. Then, after discussion of calibration and sampling techniques in Modules 27-6 and 27-7, the total measurement system is described in Module 27-8. Therefore, this module and the subsequent ones lay the foundation for the total measurement system described by Module 27-8.

This module describes gage blocks and mechanical and electronic comparators. The student/trainee should give particular attention to the application of the instruments and the sources of error with each. Also, the student/trainee should practice making measurements with these instruments to develop skill in measuring with accuracy and precision.

MODULE PREREQUISITES

The student/trainee shall have completed all previous modules of this course.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. State two purposes of gage blocks.
2. Name four tolerance grades of gage blocks, state the application of each grade, and name the specification that governs gage block accuracy.
3. List four desirable properties of gage block materials and describe the value of each property in terms of fostering gage block accuracy.
4. Describe why temperature effects on measurements must be considered and calculate temperature effects on given materials, their temperature coefficients and measuring temperature.
5. Demonstrate the ability to build a gage block combination equal to a given feature size.
6. Define comparative measurement and Abbe's law. Describe how Abbe offset contributes to error.
7. Name four advantages typical of mechanical indicators and of electronic comparators.
8. Compare the typical accuracy of mechanical indicators and electronic comparators.
9. Name at least four sources of error in measurements with (a) dial indicators, (b) test indicators, and (c) electronic comparators and describe how such sources can cause errors.
10. Define cosine error, describe how it can be eliminated, and calculate its effects given a measurement and offset values.
11. Demonstrate the ability to make measurements with gage blocks, dial indicators, test indicators, and electronic comparators.

NOTES TO INSTRUCTOR/STUDENT

Laboratory exercises are recommended to develop student/trainee skills in making measurements with the instruments described in this module. The module includes suggested exercises and procedures for this purpose although the instructor will need to tailor these to local circumstances and to add additional exercises. Advance preparation will be necessary to provide for a selection of parts to be measured; instruments to be used; standards to be used; whether the student/trainee or the instructor will apply the standard for accuracy checks.

GAGE BLOCKS

Definition and Purpose

Gage blocks are physical length standards of known accuracy. They provide for the transfer of the basic unit of length (number of wavelengths of light from krypton-86) to all types of length measurement devices. Also, gage blocks can be used directly as the measurement device.

The primary purpose of gage blocks is to make available a standard of any length by the combination of individual gage blocks into a single gage bar. To accomplish this purpose, gage blocks must meet the following criteria:

- Individual gage blocks must be available in lengths needed to achieve any combination of lengths within a designated range.
- Accuracy of individual gage blocks must be within designated tolerance limits.
- Individual blocks must be attached so closely to each other in built-up combination that the resulting bar has a length equal to the sum of the individual lengths for most practical purposes.

Styles of Gage Blocks

American National Standard, ANSI B89.1.9, specifies tolerances of size for the nongaging surfaces for two styles of gage blocks that have become essentially standardized in industry. These styles are rectangular and square with center hole.

- Rectangular - Rectangular gage blocks are most common. The non-gaging dimensions are approximately

0.355 inch by 1.187 inches. The rectangular shape readily permits obtaining very flat measuring surfaces during lapping and polishing by the manufacturers of the blocks.

- Square With Round Center Hole - This style is next most common. It is a 0.950 inch square with a 0.265 inch diameter center hole. The center hole removes the raised area that tends to occur during common lapping and polishing processes. The hole permits use of a rod and accessories for clamping a built up combination.

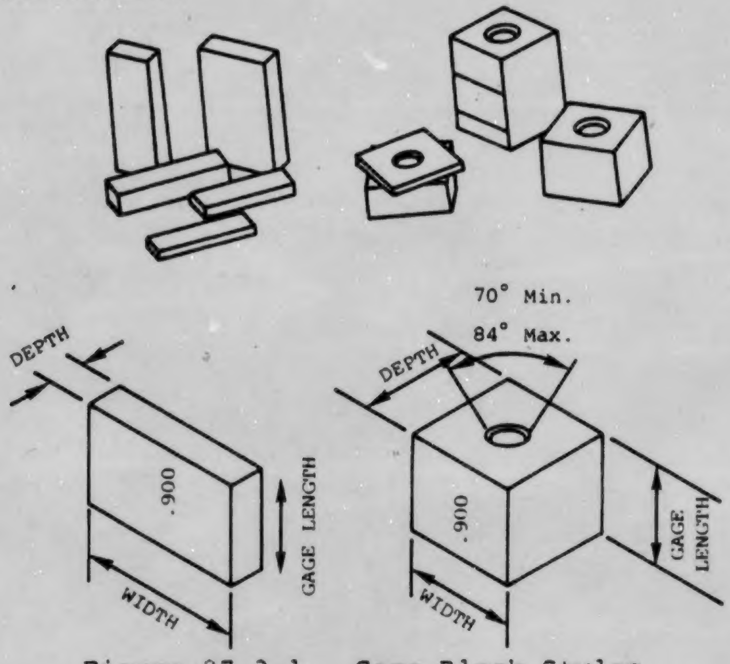


Figure 27-3-1. Gage Block Styles

Tolerance Grades of Gage Blocks

ANSI B89.1.9, Precision Inch Gage Blocks for Length Measurements, establishes four tolerance grades of gage blocks. These grades and their applications are listed in Table 27-3-1.

TABLE 27-3-1. Tolerance Grades of Gage Blocks

GRADE	FORMER GRADE (NOTE 1)	COMMON NAME	APPLICATION
0.5	AAA	Ultra Precision	Basic reference standards (grand masters)
1	AA	Laboratory	Basic reference standards
2	A+	Precision	Company tool and gage room reference blocks and inspection standards
3	A&B	Inspection and Manufacturing	Company quality assurance inspection. Company tool making and manufacturing areas

Note 1: Grades specified by ANSI B89.1.9 prior to 1973

Features of any grade of gage blocks that affect accuracy and precision are the length dimension, flatness and parallelism of the measurement surfaces, the surface finish and appearance of the measurement surfaces. The ANSI B89.1.9 tolerance limits on length, flatness and parallelism for each tolerance grade of gage blocks are listed in Table 27-3-2. These tolerances apply to the areas of gaging surfaces except for a border zone of 0.02 inch from the side face. However, the plane of the border zone is not permitted to be above the plane of the gaging surface.

Surface texture limits are established by ANSI B89.1.9 on predominant peak-to-valley roughness height and arithmetical average roughness height. The predominant peak-to-valley roughness height is limited to 2 microinches for tolerance grades 0.5 and 1, and to 4 microinches for tolerance grades 2 and 3. The average roughness heights are approximately

TABLE 27-3-2. Tolerance Grades, and Length, Flatness and Parallelism Tolerances - Tolerances in Microinches.

Nominal Size in Inches	Tolerance Grade 0.5 (Formerly Grade AAA)		Tolerance Grade 1 (Formerly Grade AA)		Tolerance Grade 2 (Formerly Grade A+)		Tolerance Grade 3 (Compromise Between Grades A + B	
	Length	Flatness & Parallelism	Length	Flatness & Parallelism	Length	Flatness & Parallelism	Length	Flatness & Parallelism
Thru 1	±1	1	±2	2	+4, -2	4	+8, -4	5
2	±2	1	±4	2	+8, -4	4	+16, -8	5
3	±3	1	±5	3	+10,-5	4	+20, -10	5
4	±4	1	±6	3	+12,-6	4	+24, -12	5
5			±7	3	+14,-7	4	+28, -14	5
6			±8	3	+16,-8	4	+32, -16	5
7			±9	3	+18,-9	4	+36, -18	5
8			±10	3	+20,-10	4	+40, -20	5
10			±12	4	+24,-12	5	+48, -24	6
12			±14	4	+28,-14	5	+56, -28	6
16			±18	4	+36,-18	5	+72, -36	6
20			±20	4	+40,-20	5	+80, -40	6

0.5 microinch for tolerance grades 0.5 and 1, and approximately 1.0 microinch for tolerance grades 2 and 3.

Measurements of gage blocks to determine their compliance with the tolerances of Table 27-3-2 may find blocks which appear to be on the tolerance limit or so close to it as to be considered "borderline". Even with precision measurement, however, some error exists in the measurement itself. To eliminate measurement disputes on borderline values, ANSI B89.1.9 allows additional tolerance in such cases as listed in Table 27-3-3.

TABLE 27-3-3. Additional Deviations for Measurement Error-Tolerance Values in Microinches

Nominal Size in Inches	Tolerance Grade 0.5		Tolerance Grade 1		Tolerance Grade 2		Tolerance Grade 3	
	Length	Flatness & Parallelism	Length	Flatness & Parallelism	Length	Flatness & Parallelism	Length	Flatness & Parallelism
Thru 4	1	1	2	1	2	1	2	2
8	-	-	3	1	6	1	6	2
12	-	-	4	1	8	1	8	2
20	-	-	5	1	10	1	10	2

ANSI B89.1.9 establishes limits for additional features as follows:

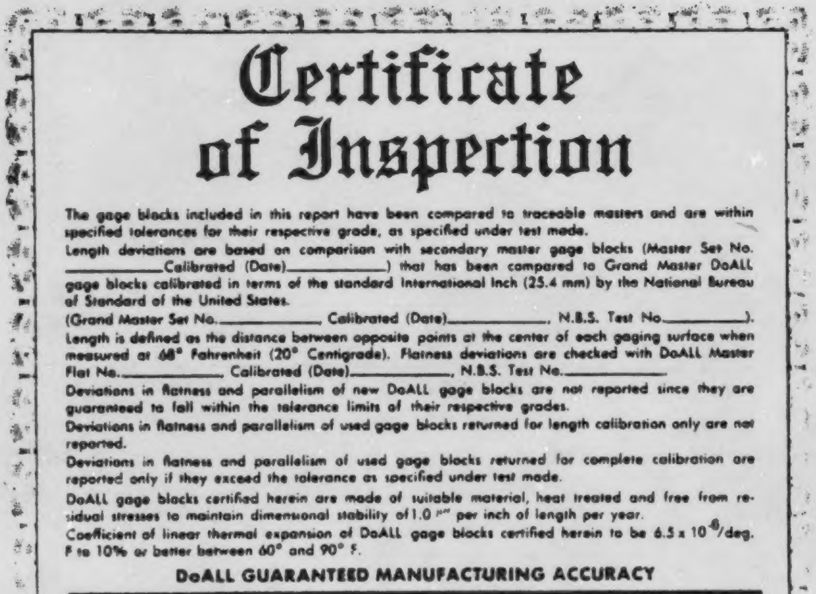
1. Gaging surfaces shall be free from burrs, nicks, fractures, sharp corners, raised edges, corrosion, lapping streaks, and other defects which may affect accuracy or serviceability.
2. Fine lapping scratches and a few stray scratches not exceeding 12 μ inch are permissible provided the peak to valley surface texture requirement is met.
3. Sides of gage blocks 0.4 inch and longer shall be square with the gaging surfaces and with each other within 5 minutes of arc.
4. Tolerances apply at 68 degrees F.

In addition, ANSI B89.1.9 identifies accuracy level grades as listed in Table 27-3-4. Accuracy level grade is the numerical classification which defines the accuracy capability of a gage block when it is used individually. The classification number is expressed in microinches, and is equal to the greater of the maximum parallel deviation or the sum of the maximum flatness deviations of each gaging surface.

TABLE 27-3-4. Accuracy Level Grade Tolerance Values for Flatness and Parallelism (No Allowance for Measurement Error)

Accuracy Level Grade Number	Maximum Parallelism Deviation	Maximum Flatness Deviation Each Surface
	Values In Microinches	
1µ"	1.0	0.5
2µ"	2.0	1.0
3µ"	3.0	1.5
4µ"	4.0	2.0
5µ"	5.0	2.5

Whether tolerance grades or accuracy grades are ordered, manufacturers provide certification of the blocks. A typical certification, courtesy of DoAll, is shown in Figure 27-3-2.



Certificate of Inspection

The gage blocks included in this report have been compared to traceable masters and are within specified tolerances for their respective grade, as specified under test mode.

Length deviations are based on comparison with secondary master gage blocks (Master Set No. ____________ Calibrated (Date)____________) that has been compared to Grand Master DoALL gage blocks calibrated in terms of the standard International Inch (25.4 mm) by the National Bureau of Standard of the United States.

(Grand Master Set No.____________, Calibrated (Date)____________, N.B.S. Test No.____________).

Length is defined as the distance between opposite points at the center of each gaging surface when measured at 68° Fahrenheit (20° Centigrade). Flatness deviations are checked with DoALL Master Flat No.____________, Calibrated (Date)____________, N.B.S. Test No.____________

Deviations in flatness and parallelism of new DoALL gage blocks are not reported since they are guaranteed to fall within the tolerance limits of their respective grades.

Deviations in flatness and parallelism of used gage blocks returned for length calibration only are not reported.

Deviations in flatness and parallelism of used gage blocks returned for complete calibration are reported only if they exceed the tolerance as specified under test mode.

DoALL gage blocks certified herein are made of suitable material, heat treated and free from residual stresses to maintain dimensional stability of 1.0 µ" per inch of length per year.

Coefficient of linear thermal expansion of DoALL gage blocks certified herein to be 6.5×10^{-6}/deg. F to 10% or better between 60° and 90° F.

DoALL GUARANTEED MANUFACTURING ACCURACY

DoALL GRADES	FED. SPEC GRADE	Length tolerances per Inch			
		010 to 2 In.	3 to 8 In.	10 to 12 In.	16 to 20 In.
AA	#1	+ .000002	+ .000001 - .000001	+ .000001 .000001	+ .000001 - .000001
A+	#2	+ .000004 .000002	+ .0000025 .000001	+ .000002 .000001	+ .000002 .000001

DoALL GRADES	FED. SPEC. GRADE	Flatness & Parallelism		** Surface finish AA (Arithmetic Average)	** Surface texture Predominant peak to valley height
		100 to 2 In	Over 2 In		
AA	#1	.000002	.000003	4	1.6
A+	#2	.000003	.000004	4	1.6

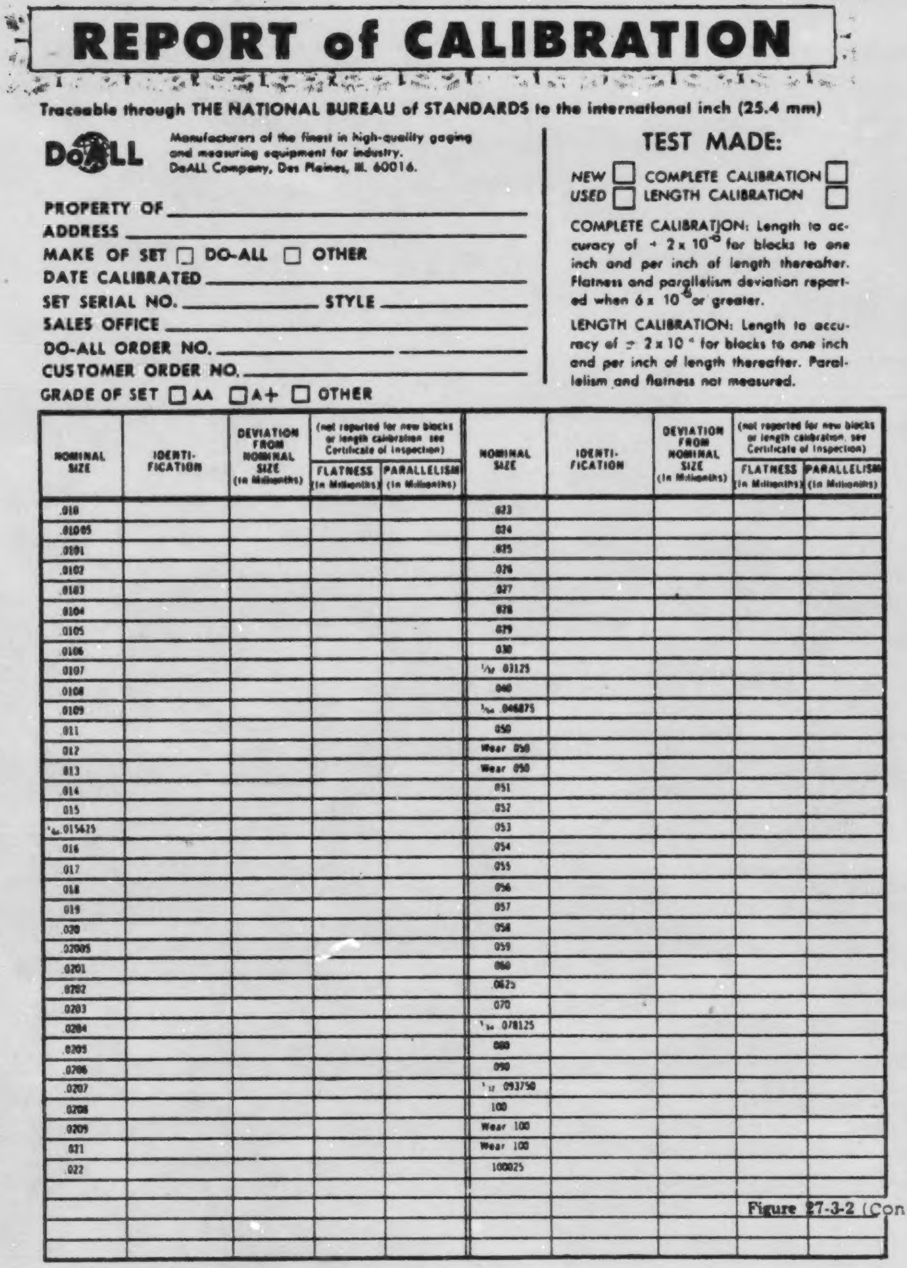
Russell F. Stark Chief Inspector

DoALL Gage Laboratories
Savage, Minnesota
55378

(Courtesy of DoAll)

** Surface Finish and Surface Texture in Micro Inches

Figure 27-3-2. Typical Certification of Gage Block Sets



REPORT of CALIBRATION

Traceable through THE NATIONAL BUREAU of STANDARDS to the international inch (25.4 mm)

DoALL Manufacturers of the finest in high-quality gaging and measuring equipment for industry.
DoALL Company, Des Plaines, Ill. 60016.

PROPERTY OF ______________________
ADDRESS ______________________
MAKE OF SET ☐ DO-ALL ☐ OTHER
DATE CALIBRATED ______________________
SET SERIAL NO. ____________ STYLE ____________
SALES OFFICE ______________________
DO-ALL ORDER NO. ____________ ____________
CUSTOMER ORDER NO. ______________________
GRADE OF SET ☐ AA ☐ A+ ☐ OTHER

TEST MADE:

NEW ☐ COMPLETE CALIBRATION ☐
USED ☐ LENGTH CALIBRATION ☐

COMPLETE CALIBRATION: Length to accuracy of $\pm 2 \times 10^{-6}$ for blocks to one inch and per inch of length thereafter. Flatness and parallelism deviation reported when 6×10^{-6} or greater.

LENGTH CALIBRATION: Length to accuracy of $\pm 2 \times 10^{-6}$ for blocks to one inch and per inch of length thereafter. Parallelism and flatness not measured.

NOMINAL SIZE	IDENTI-FICATION	DEVIATION FROM NOMINAL SIZE (in Millionths)	(not reported for new blocks or length calibration see Certificate of Inspection)		NOMINAL SIZE	IDENTI-FICATION	DEVIATION FROM NOMINAL SIZE (in Millionths)	(not reported for new blocks or length calibration, see Certificate of Inspection)	
			FLATNESS (in Millionths)	PARALLELISM (in Millionths)				FLATNESS (in Millionths)	PARALLELISM (in Millionths)
.010					.023				
.01005					.024				
.0101					.025				
.0102					.026				
.0103					.027				
.0104					.028				
.0105					.029				
.0106					.030				
.0107					1/32 .03125				
.0108					.040				
.0109					3/64 .046875				
.011					.050				
.012					Wear .050				
.013					Wear .050				
.014					.051				
.015					.052				
1/64 .015625					.053				
.016					.054				
.017					.055				
.018					.056				
.019					.057				
.020					.058				
.02005					.059				
.0201					.060				
.0202					.0625				
.0203					.070				
.0204					5/64 .078125				
.0205					.080				
.0206					.090				
.0207					3/32 .093750				
.0208					.100				
.0209					Wear .100				
.021					Wear .100				
.022					.100025				

Figure 27-3-2 (Cont.)

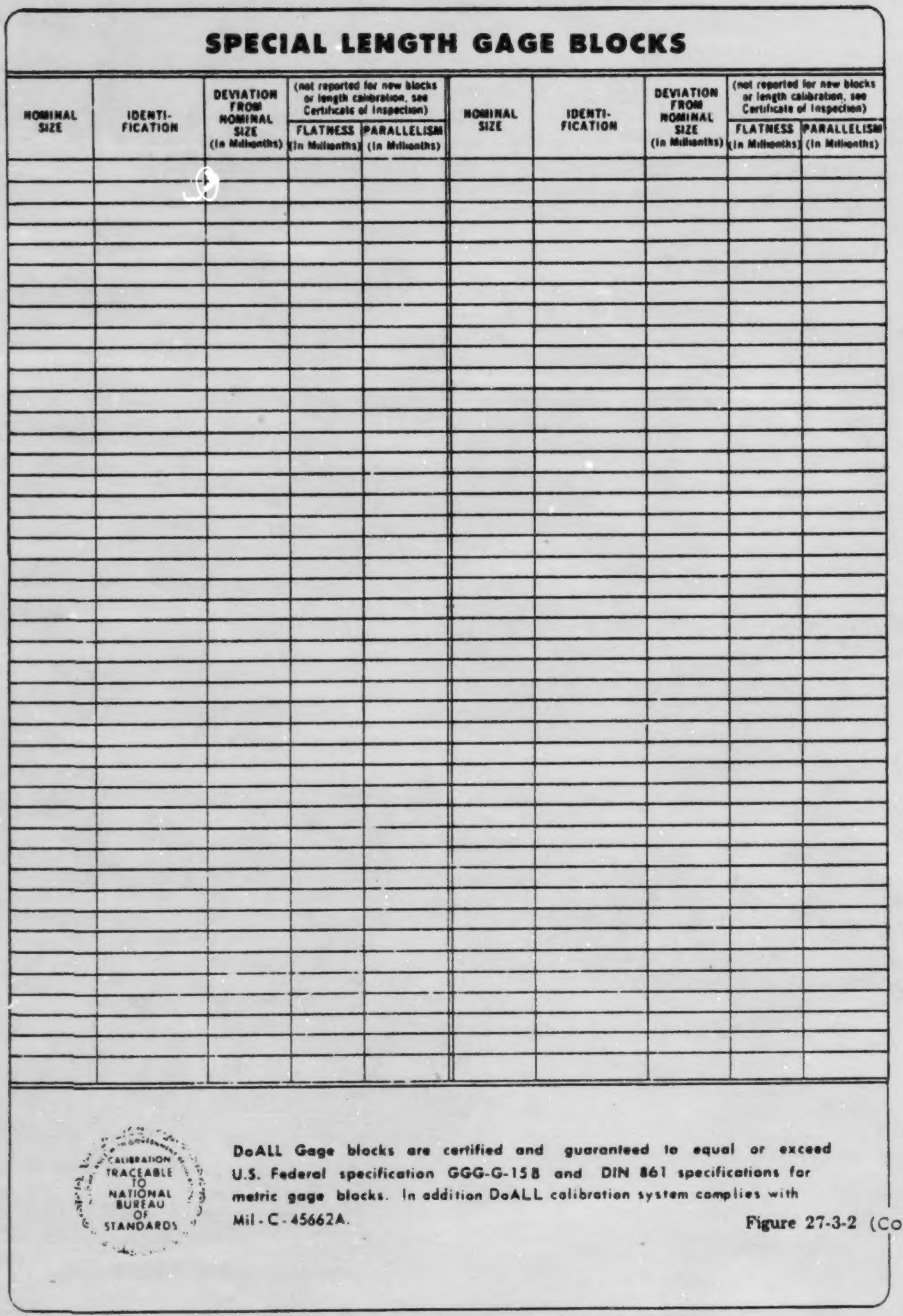
Figure 27-3-2. (Cont.)

STANDARD GAGE BLOCK CALIBRATION (CONTD.)

NOMINAL SIZE	IDENTI-FICATION	DEVIATION FROM NOMINAL SIZE (in Millionths)	(not reported for new blocks or length calibration, see Certificate of Inspection)		NOMINAL SIZE	IDENTI-FICATION	DEVIATION FROM NOMINAL SIZE (in Millionths)	(not reported for new blocks or length calibration, see Certificate of Inspection)	
			FLATNESS (in Millionths)	PARALLELISM (in Millionths)				FLATNESS (in Millionths)	PARALLELISM (in Millionths)
.100050					.141				
.100075					.142				
.1001					.143				
1002					.144				
.1003					.145				
.1004					.146				
.1005					.147				
.1006					.148				
1007					.149				
.1008					.150				
1009					160				
.101					.170				
102					.180				
.103					.190				
104					200				
.105					.200010				
106					200020				
.107					.200030				
.108					200040				
109					.200050				
.109375					200060				
.110					.200070				
.111					.200080				
.112					.200090				
.113					.250				
114					300				
115					350				
.116					375				
.117					.400				
118					.450				
.119					500				
120					550				
121					600				
122					650				
.123					700				
124					750				
.125					800				
126					850				
.127					900				
.128					950				
129					1.000				
.130					2.000				
.131					3.000				
.132					4.000				
.133					5.000				
134					6.000				
135					7.000				
136					8.000				
137					10.000				
138					12.000				
139					16.000				
140					20.000				

Figure 27-3-2 (Cont.)

Figure 27-3-2. (Cont.)



SPECIAL LENGTH GAGE BLOCKS

NOMINAL SIZE	IDENTIFICATION	DEVIATION FROM NOMINAL SIZE (In Millionths)	(not reported for new blocks or length calibration, see Certificate of Inspection) FLATNESS (In Millionths)	PARALLELISM (In Millionths)	NOMINAL SIZE	IDENTIFICATION	DEVIATION FROM NOMINAL SIZE (In Millionths)	(not reported for new blocks or length calibration, see Certificate of Inspection) FLATNESS (In Millionths)	PARALLELISM (In Millionths)

CALIBRATION TRACEABLE TO NATIONAL BUREAU OF STANDARDS

DoALL Gage blocks are certified and guaranteed to equal or exceed U.S. Federal specification GGG-G-15B and DIN 861 specifications for metric gage blocks. In addition DoALL calibration system complies with Mil-C-45662A.

Figure 27-3-2 (Cont.)

140

Figure 27-3-2. (Cont.)

Gage Block Materials

Desired properties of materials used for manufacture of gage blocks include high hardness, excellent stability, homogeneity, and good corrosion resistance. High hardness is desirable to resist wear and to accept extremely fine surface finish. Stability is necessary to maintain accuracy of the gage block size. Gradual phase transformations of the crystalline structure and internal stresses contribute to unstability. Homogeneity is of concern primarily with powder metals and pertains to the ability to meet surface texture requirements with powder metals. Good corrosion resistance is desirable to extend life of gage blocks. Thermal expansion of gage block materials can also introduce errors as described in this module. Materials used in the manufacture of gage blocks represent compromises with these properties because no single material offers the best of each desired property.

- Tool Steel - Tool steel offers a high hardness of 65 Rockwell C and can accept a fine surface finish. While its stability is good, it is susceptible to gradual phase transformation that results in shrinkage or growth of the block. Its corrosion resistance is only fair.
- Chrome-Plated Steel - The chrome plating over the basic steel core increases resistance to wear and corrosion. High hardness is retained and fine surface finishes are attainable. Stability equals that of the tool steel.
- Stainless Steel - Stainless steel blocks offer the excellent wear and corrosion resistance of chrome plated tool steel blocks. Martinsitic stainless

steel is commonly used to provide a high hardness of 69-70 Rockwell C, and to accept exceptionally fine surface finish.

- Tungsten Carbide or Chromium Carbide - Manufacture of these gage blocks employs powder metallurgy technology that sinters metallic particles with cobalt or nickel binder to form a solid, non-crystalline metal. While such blocks are expensive, they have outstanding wear properties, and excellent stability. Hardness is in the range of 88-92 Rockwell A. Proneness for chipping and difficulty in achieving surface homogeniety are drawbacks.

Accuracy of gage blocks is affected by wear, growth or shrinkage with time, and corrosion. Good handling and storage practices minimize wear and corrosion, but stability is inherent with the type of material and the processing performed on the material. Because of instability, accuracy of gage blocks must be periodically determined even when the blocks are seldom used.

Temperature Effects

Gage block sizes are measured and certified at the temperature of 68°F (20°C) established by International Standard ISO-1. However, each particular gage block material and each workpiece material has its own coefficient of thermal expansion. If measurements occur at 68°F, any differences in thermal expansion coefficients between gage blocks and the item measured are of no consequence. By necessity, though, measurements are often made in an uncontrolled temperature environment. In such cases, the coefficient of expansion of both gages and the workpiece must be considered. For accurate results, steel gage blocks used to measure a steel workpiece will usually expand a like amount as the workpiece and produce fairly accurate readings. Conversely, steel gage blocks used to measure an aluminum workpiece would necessitate consideration of measurement temperature, size of work, and coefficient of thermal expansion for both materials. In all measurements, three rules apply with respect to temperature effects on the accuracy of the measurement:

- Both the measuring device and the item to be measured must be at the same temperature.
- Measurements at 68°F do not require correction for thermal effects.
- Measurements at other than 68°F require calculation of thermal effects to determine if correction is necessary.

Notice that the third rule does not mean that corrections for thermal effects are always necessary. Instead, the effects must be determined. Corrections are necessary only if the effects jeopardize the desired accuracy of the measurement. The effect is calculated by the formula:

$$MD = L(k_g - k_w)(T - 68°F) \qquad \text{(Equation 27-3-1)}$$

Where:

MD = measuring difference in inches of the measurement at temperature T as compared to the same measurement at 68°F.

L = length of the measurement in inches.

k_g = thermal expansion coefficient of the gage in inch per inch of length per°F.

k_w = thermal expansion coefficient of the workpiece in inch per inch of length per °F.

T = temperature in at which the measurement is made.

Whenever temperature effects are to be calculated, careful selection of thermal expansion coefficients is necessary. The exact alloy and condition of material must be known and coefficients must represent the specific material. Also, since some published coefficients are in error by as much as ±10%, several modern publications of coefficients should be consulted. The following example uses representative coefficients which are not intended for other applications.

EXAMPLE:

Problem: What is the true length (Length at 68°F) of the aluminum bar?

Given: An aluminum bar is measured with 52100 steel gage blocks at 78°F, and is found to be 4.5000 inches long. The coefficients of thermal expansion for the aluminum and steel are 12.8×10^{-6} and 6.4×10^{-6} inch/inch/°F respectively.

Solution: Measuring difference = (length) x (expansion coefficient difference) x (temperature deviation from 68°F)

$= 4.5 \text{ inches} \times (6.4 - 12.8) \times 10^{-6} \text{ inch/inch/°F} \times (78°F - 68°F)$

$= -.000288$ inch, rounded to $-.0003$

Therefore, the length of the bar at 68°F is 4.5000 - 0.0003 = 4.4997 inches.

NOTE: A decision to apply the correction must consider the measured value in relation to the tolerance limits of the item being measured. If the aluminum bar is acceptable from 4.4990 to 4.5000 inches, the correction factor would definitely be applied. But, if the bar is acceptable from 4.4990 to 4.5010, a correction is unnecessary.

Coefficients of thermal expansion for each alloy can be found in most metals and thermodynamics text books. When calculating effects of thermal expansion on measurements, care must be exercised to select the coefficients that apply to the specific alloys of the gage and workpiece. In general, as measurement length increases and tolerance decreases, thermal expansion plays a larger role.

Building the Gage Block Combination

Sets of gage blocks permit building a length standard to any dimension within the range of the set. Number of blocks and their sizes of typical gage block sets are shown in Table 27-3-5. A typical set is pictured in Figure 27-3-3.

TABLE 27-3-5. Typical Gage Block Sets

PIECES IN THE SET	NUMBER OF BLOCKS PER SERIES	SIZE RANGE INCH	SERIES INCREMENT INCH
15	4	0.0501 to 0.0503 plus 0.0506	0.0001
	4	0.051 to 0.053 plus 0.056	0.001
	4	0.010 to 0.030 plus 0.060	0.010
	4	0.100 to 0.300 plus 0.600	0.100
		1.000 to 3.000	1.000
35	9	0.1001 to 0.1009	0.0001
	9	0.101 to 0.109	0.001
	9	0.110 to 0.190	0.010
	5	0.100 to 0.500	0.100
	3	1.000 to 3.000	1.000
81	9	0.1001 to 0.1009	0.0001
	49	0.101 to 0.149	0.001
	19	0.050 to 0.950	0.050
	4	1.000 to 4.000	1.000

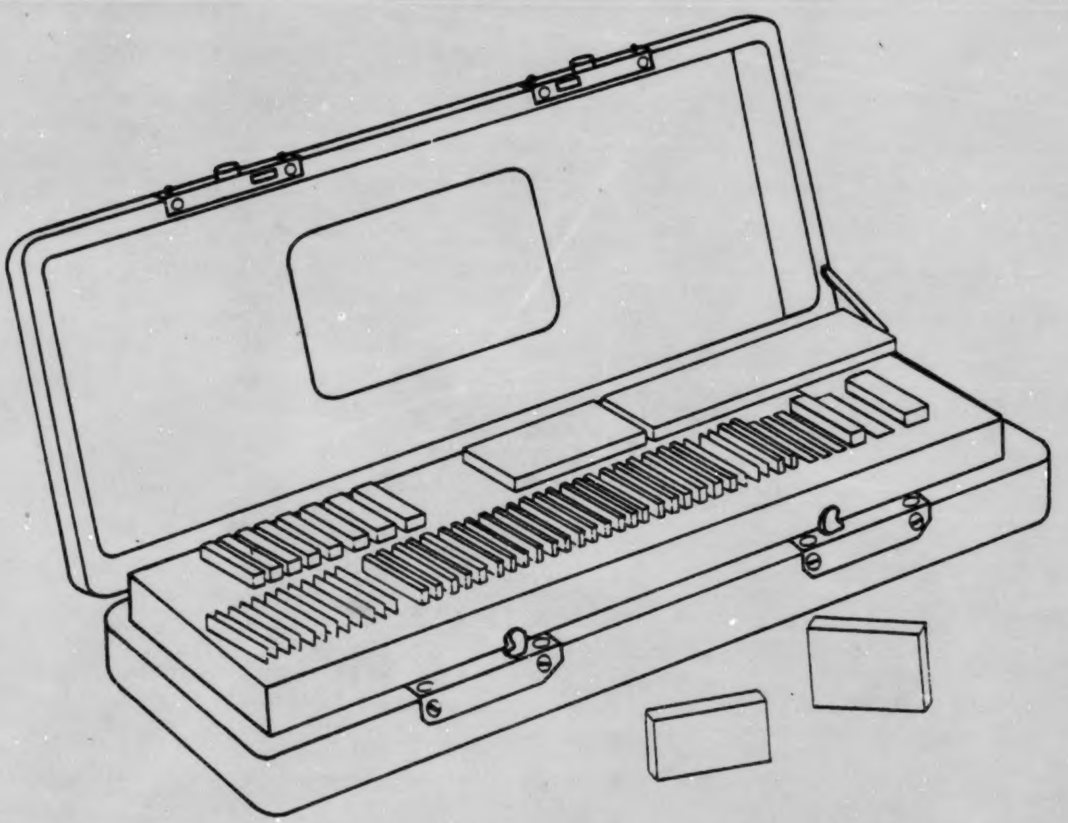
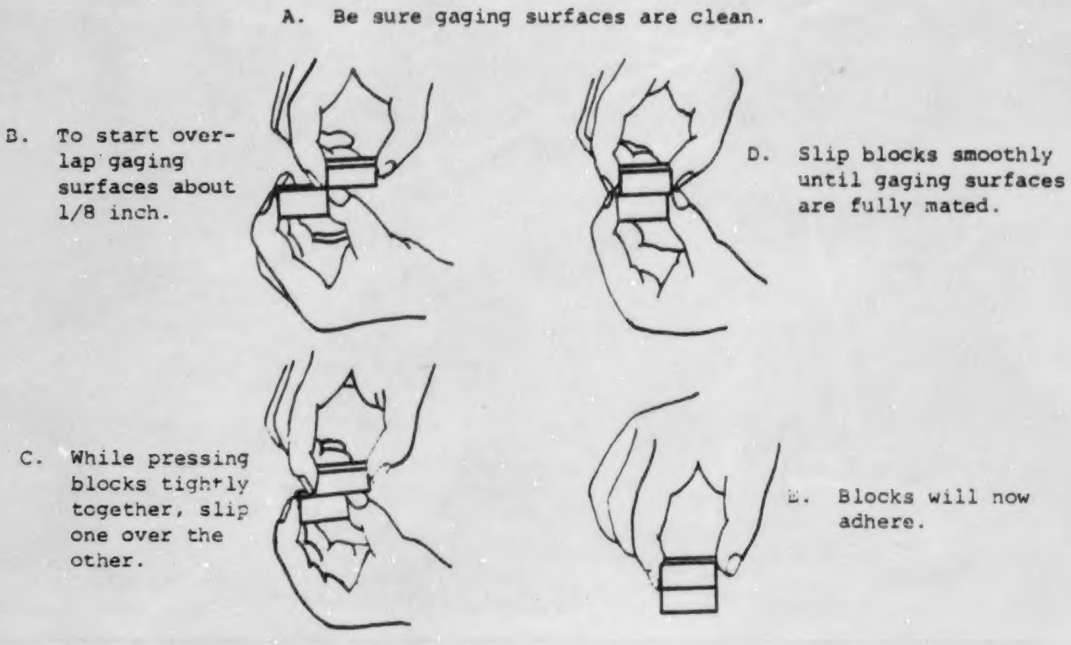


Figure 27-3-3. Gage Block Sets (Courtesy of DoAll)

Gage block sets permit building many combinations of length standards by their "wringability". Wringability is the characteristic of gage blocks which permits placing blocks in intimate contact such that their gaging surfaces adhere. Wringability is provided by the excellent flatness and fine surface texture required of blocks. It is a phenomenon of flat, smooth surfaces when they are brought into intimate contact. It is not dependent on magnetism or air pressure; instead, intimate contact of the surfaces is required.

Individual blocks are "wrung" together to build the desired combination. Gage blocks must be cleaned and examined for burrs prior to wringing. Minute quantities of foreign materials such as dirt, grit, and grease will introduce error, and also damage the surface finish of the measuring surfaces. Kerosene or Stoddard solvent are acceptable cleaning agents. Also, soft, lint-free cloths or chamois should be used. Burrs may be removed by white Arkansas sintered aluminum oxide, or a granite deburring stone. If the gage blocks are clean and free from burrs, they are wrung together using the technique shown in Figure 27-3-4. A thin oil film tends to make the wringing easier. A drop or two of oil is applied with a dropper and spread over the surface with a clean cloth. Once wrung, the oil film is squeezed out such that the separation of the blocks is on the order of .000002 inch or less.



A. Be sure gaging surfaces are clean.

B. To start overlap gaging surfaces about 1/8 inch.

D. Slip blocks smoothly until gaging surfaces are fully mated.

C. While pressing blocks tightly together, slip one over the other.

E. Blocks will now adhere.

Figure 27-3-4. Wringing Technique

Five basic rules apply to building the gage block combination:

1. Use the minimum number of blocks.
2. Write the desired dimension and the blocks to be used on paper to ensure both the minimum number of blocks and use of the proper block.
3. Start by eliminating the last place decimal of the desired dimension and continue to select gage block sizes that will eliminate the remaining last place decimals. (In general, select the largest possible block.)
4. Consider the thermal effects of handling the gage blocks. Either use insulated forceps for wringing or place the wrung stack on a chill block to permit thermal equalization with ambient.
5. After completion of the measurement, disassemble the combination, clean the blocks, apply a thin oil coating, and return them to their case. (Moisture trapped between blocks will accelerate corrosion.)

Application of Gage Blocks

Because of rigid standards of product tolerances and the use of very sensitive comparator instruments, the use of gage blocks in actual production is becoming more general. Some of the more common uses are:

a. Direct measurement of distances between parallel surfaces, widths of grooves and keyways.
b. Adjusting and checking mechanical measuring tools.
c. Assembling limit gages.

d. Establishing distances for transfer of dimensions.

e. Angle measurements by the sine bar method.

EXAMPLE:

Problem: Build a gage block length standard equal to 3.3875 inches.

Given: A 35 piece gage block set (See Table 27-3-2).

Solution:

Desired Dimension	3.3875	
Eliminate the 0.0001 inch digit	-0.1005	(first block selected)
	3.2870	
Eliminate the 0.001 inch digit	-0.107	(second block selected)
	3.180	
Eliminate the 0.010 inch digit	-0.180	(third block selected)
	3.000	
Complete with a 3.000 inch block	-3.000	(fourth block selected)
	0.000	

EXAMPLE:

Problem: Build a gage block length standard equal to 3.3875 inches.

Given: The remainder of the 35 piece gage block set given in the previous example, i.e., the 0.1005, 0.107, 0.180, and 3.000 blocks are no longer available.

Solution:

Desired dimension	3.3875	
Eliminate the 0.0001 inch digit	-0.1001	(first block)
	-0.1004	(second block)
	3.1870	
Eliminate the 0.001 inch digit	-0.105	(third block)
	-0.102	(fourth block)
	2.980	
Eliminate the 0.010 inch digit	-0.130	(fifth block)
	-0.150	(sixth block)
	2.700	
Eliminate the 0.100 inch digit	-0.500	(seventh block)
	-0.200	(eighth block)
Eliminate the inches	-2.000	(ninth block)
	0.000	

NOTE: Had the 81 piece set been given for both examples, the two combinations could have been built with four and six blocks.

COMPARISON MEASUREMENT WITH MECHANICAL INDICATORS

Definition

Mechanical indicators sense, amplify, and indicate displacement from an established datum. Such displacement is indicated as either positive or negative with respect to the datum. Thus, the measurement obtained is an amount and direction of the deviation from an established size. The measurement must always be in comparison to an established size and, therefore, is known as comparative measurement.

Mechanical indicators are classified as dial indicators and test indicators. The mechanical dial indicator is a mechanical instrument for sensing and measuring distance variations that are parallel to the axis of the sensor. The mechanical test indicator is a mechanical instrument for sensing and measuring distance variations that are essentially vertical to the axis of the sensor.

Advantages of Mechanical Indicators

Mechanical indicators offer excellent accuracy and precision for a wide range of applications. In comparison to other types of measuring devices of similar accuracy and precision, mechanical indicators typically enjoy the following advantages although the particular design may not possess all these advantages:

- Long Measuring Range - Certain designs of dial indicators have measuring ranges of 20 or more revolutions of the indicator hand.
- Small Size - The small overall size (particularly of test indicators) permits access to space restricted areas and application of several indicators in close proximity.
- Controlled Measuring Force - The operator's feel is eliminated by the positive contact and fixed measuring force inherent in the instrument.
- Ruggedness - The shock resistance of many mechanical indicators make them well suited for shop measurements where considerable machine vibrations are present.
- Independence of Power Supply - Mechanical indicators can be set up anywhere since power sources are not used. Also, electrical and magnetic fields do not affect the accuracy of the measurement.

- Stability - Drift, which is present in electrical and fluid pressure indicators, is not present in mechanical indicators.
- Economy - Initial cost is comparatively low and necessary maintenance can normally be accomplished locally.

DIAL INDICATORS

Description:

A dial indicator is a comparative measuring device that senses distance variations parallel to the axis of its spindle (sensor), amplifies the variation through its internal mechanism and provides readout by an indicating hand on a graduated dial. As shown in Figure 27-3-5, the key functional parts that are externally visible are the spindle, bezel, bezel clamp, dial face, and indicating hand.

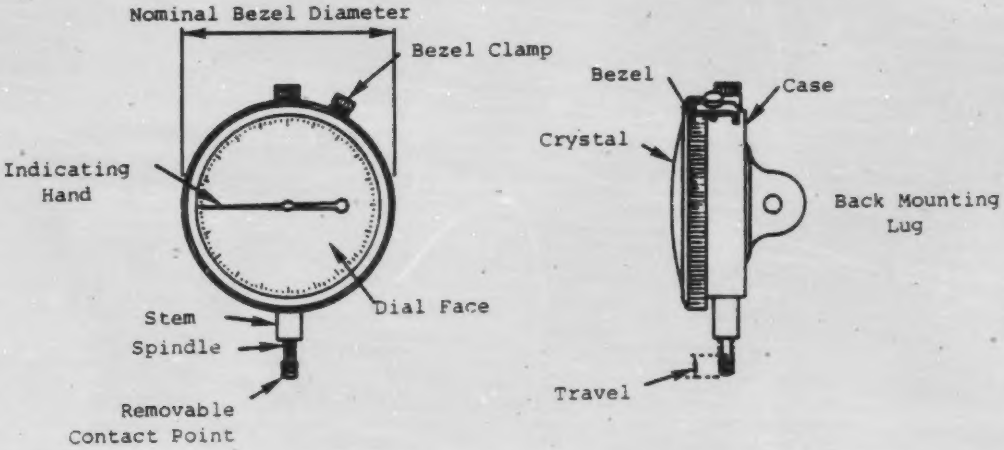

Nominal Bezel Diameter
Bezel Clamp
Indicating Hand
Dial Face
Stem
Spindle
Removable Contact Point
Bezel
Case
Crystal
Back Mounting Lug
Travel

Figure 27-3-5. Dial Indicator Nomenclature

Referring to Figure 27-3-5, the spindle with its contact point is the sensor. The bezel and dial face are integral and rotatable. With the dial indicator "set" to the desired size, the bezel is rotated until the zero point of the dial face lies directly under the indicating hand. With the dial indicator "zeroed" in this manner, the bezel clamp is tightened to fix the bezel at the set dimension.

Fixturing of dial indicators to permit zeroing at a desired size is accomplished by mounting by the stem or by the back mounting lug. The fixturing may establish the reference datum or may permit use of a reference datum on the item to be inspected. The dial indicator is zeroed by use of gage blocks or by datum features of the item to be inspected.

Zeroing of indicators establishes the reference boundary from which measurements are made. Zeroing is not to be confused with calibration. The accuracy and precision of the indicator are determined by calibration, while zeroing merely sets the indicator to a desired point of reference.

Table 27-3-6 shows common internal mechanisms of dial indicators.

Accuracy and Precision of Dial Indicator

Dial indicators of acceptable industrial quality perform with reliable accuracy and precision. A typical accuracy criteria for dial indicators is that the reading must be within one graduation of the dial (plus or minus) of the true size for each 2-1/3 revolutions of the pointer. Another common method of specifying accuracy is by the limit of acceptable error expressed as a percentage of full scale. For example, if an indicator having a range of .020 inch has .001 inch error at full scale, the indicator is stated to have accuracy within 5% (.001 ÷ .020 x 100% = 5%). If accuracy of the dial indicator is plotted against revolutions of the indicating hand, the results may indicate that the error is evenly spread throughout the range or occurs at various intervals of rotation. Such plots are helpful in determining the sector that is most linear in response.

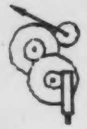
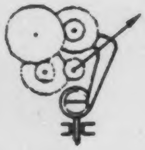
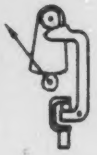
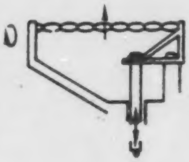
DESIGNATION	SCHEMATIC SKETCH	OPERATIONAL DESCRIPTION	FORM OF DISPLAY	SMALLEST GRADUATION	MEASURING RANGE
Rack and Pinion		Spindle drives a rack which rotates a pinion which is part of an amplifying gear train.	Dial	From 0.0001 to 0.001 inch	0.025 to 0.250 inch Specials to several inches
Cam and Gear Train		Spindle moves a cam which transmits the motion to the amplifying gear train.	Dial	From 0.00005 to 0.0001 inch	From 0.010 to 0.025 inch
Compound Levers		Sensor drives levers that couple with compound action and are connected through segments and pinions.	Sector	From 0.00002 to 0.0005 inch	From 0.002 to 0.020 inch
Twisted Taut Strip		The twisted taut band rotates proportionally to the strain introduced by the sensor.	Sector	From 0.00001 to 0.0005 inch	From 0.0012 to 0.040 inch

TABLE 27-3-6. Common Internal Mechanisms of Dial Indicators

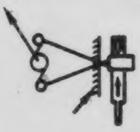
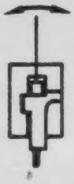
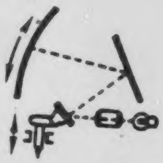
DESIGNATION	SCHEMATIC SKETCH	OPERATIONAL DESCRIPTION	FORM OF DISPLAY	SMALLEST GRADUATION	MEASURING RANGE
Lever Combined with band Wound Around Drum		Movement of the gage spindle tilts hinged block; this causes swing of the fork which induces rotation of the drum.	Large Sector	From 0.00001 to 0.0002 inch	From 0.0012 to 0.020 inch
Reeds Combined with Optical Display		Parallelogram reed transfers spindle movement to a deflecting reed with extension carrying a target which partially obstructs the optical path of a light beam.	Shadow on the Face of a Sector	From 0.00001 to 0.0001 inch	From 0.0005 to 0.008 inch
Tilting Mirror Projecting Light Spots		Spindle movement transferred by lever action tilts intermediate mirror thereby changing position of the projected light spot on the graduated screen.	Stepped Light Spot on the Face of a Sector	From 0.000025 to 0.00005 inch	From 0.0028 to 0.0055 inch

TABLE 27-3-6. Common Internal Mechanisms of Dial Indicators (Continued)

Expected precision of dial indicators is established as 1/5th of an increment of the dial face. Therefore, for the dial indicator having graduations of 0.001 inch, acceptable precision is repeatability of measurements within 0.0002 inch.

Abbe's Law

In the late 1800's, Ernest Abbe formalized the relationship which is known as "Abbe's law", "Abbe's principle" or "the comparator principle". It is conveniently summarized by Ted Busch[1] as follows:

> "Maximum accuracy may be obtained only when the standard is "in line" with the axis of the part being measured."

The work "standard" in the above summarization may be taken to mean the actual indicated reading on the measuring device. This "in line" condition would take place in measurements with a micrometer. With a vernier caliper, the indicated reading would be along a line parallel to the true axis of the unit being measured because the scale of the vernier caliper is displaced at some distance from the contact jaws that actually touch the unit being measured and thus the "in line" condition of Abbe would not be met.

Ted Busch[1] goes on to give an example of the proper application of Abbe's Law using the vernier caliper, as previously discussed in Module 27-2 of this course.

There are four essential points to consider when applying Abbe's Law to a measuring instrument such as a vernier caliper. These are:

---

[1] Ted Busch, *Fundamentals of Dimensional Metrology*, Delmar Publishers

FOUR ESSENTIAL POINTS

1. Line of measurement is shortest distance separating the reference point and measured point. If part is rectangular, this line is perpendicular to the reference edges.

THEREFORE:

2. Line of measurement must lie in plane of caliper.
3. Line of measurement must be parallel to beam of caliper.
4. All deviations from the above will be included as error in the caliper reading.

Figure 27-3-6 shows how to apply Abbe's law in order to make a proper measurement using the vernier caliper.

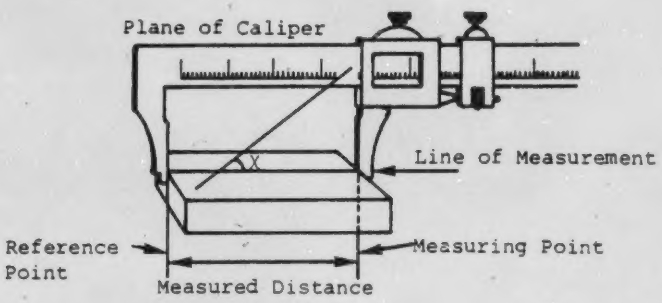
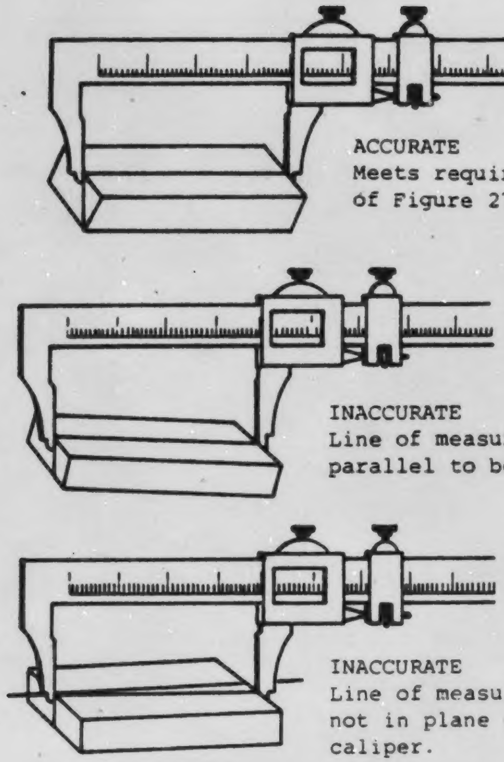


Figure 27-3-6. Proper measurement technique using the vernier caliper.

The proper caliper alignment is essential for an accurate measurement as given by Abbe's Law. Figure 27-3-7 shows other vernier caliper alignment geometries. Whenever the line of measurement is not parallel to the beam of the caliper then the measurement will be inaccurate. While the caliper is used here to illustrate Abbe's law, the essential points apply to all dimensional measurement devices.



ACCURATE
Meets requirements of Figure 27-3-6

INACCURATE
Line of measurement not parallel to beam.

INACCURATE
Line of measurement not in plane of caliper.

Figure 27-3-7. Vernier caliper alignment showing the importance of positional geometry for making accurate measurements.

Sources of Error of Dial Indicators

Sources of error in measurements with dial indicators stem from inherent errors of the instrument and from the inspection procedure. With regard to the instrument, the total effect of errors is determined when the dial indicator is calibrated. If accuracy or precision is beyond expectations, adjustment or repair is made. Sources of instrument error include:

- Clearance in teeth mesh of the internal mechanism - Such clearance permits backlash and/or lagging response which affect linearity and repeatability.
- Imperfect gear form of the internal mechanism - Imperfect gear form provides cumulative error with travel and is, therefore, most prevalent in dial indicators with extended range.
- Clearance of the spindle with its guide - Such clearance can affect the positional relationship from contact tip to the initial pinion (Abbe's law).
- Clearance of bearings and wear of internal mechanism - Jewelers' bearings are frequently used to provide better accuracy. However, such bearings may crack from shock and cause sticking.

With regard to the measurement procedure, the two largest sources of error are the fixturing and positioning of items to be insepcted. In many applications, the dial indicator and associated fixturing are one integral inspection device. In such cases, calibration of the dial indicator includes calibration of the device. Where an assortment of fixturing is used, each setup of fixturing and dial indicator is calibrated prior to its use as an inspection device, and periodically thereafter. Flexure of fixturing must be minimized to reduce error. With respect to positioning of items to be inspected, attention is given to proper contact with the reference datum and alignment between the sensor of the dial indicator and the axis of the part (Abbe's law).

Another procedural error is use of mechanical indicators for direct measurement rather than comparative measurement. It must be remembered that mechanical indicators are comparative measuring devices and that their greatest accuracy is that portion of range close to zero rather than the portion toward full range. If comparators are used for direct measurement, the larger error toward the full range tends to be ignored and erroneous measurements invariably result.

Applications of Dial Indicator Instruments

An extremely broad application of dial indicators exists. A few of the common dial indicator instruments are the bench comparator gage, dial snap gage, dial depth gage, and dial bore gage.

Dial Comparator Gage

Dial indicators used on a stand which provides a reference datum that supports the item to be measured constitute a bench comparator gage. Referring to Figure 27-3-8, which shows a typical bench comparator, the base supports a precision finished reference surface to hold the workpiece. A column, rising from the rear of the base provides for vertical adjustment of the gage head, which supports the dial indicator above the reference surface. The gage head is adjusted to the proper height by zeroing the indicator to a master standard of the specified workpiece size. As the workpieces are placed in the gage, size variations from the standard register below or above zero on the dial.

Dial Snap Gage

This instrument utilizes the dial indicator for rapidly checking a number of external features of a workpiece with ease and precision. Referring to Figure 27-3-9, which pictures

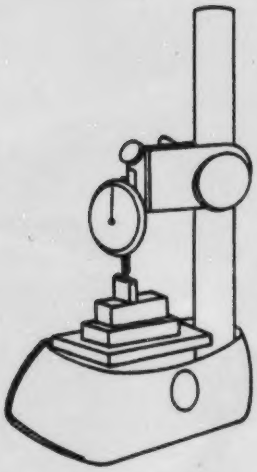


Figure 27-3-8. Bench Comparator

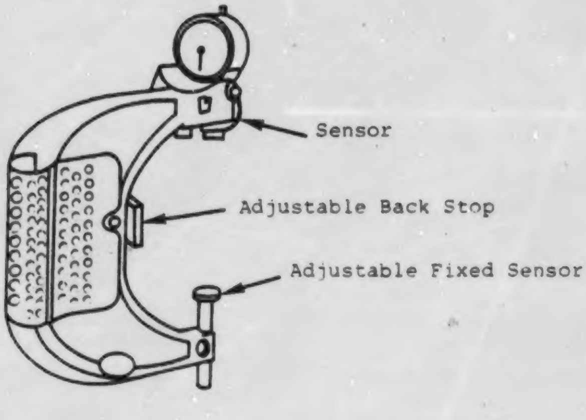

Sensor
Adjustable Back Stop
Adjustable Fixed Sensor

Figure 27-3-9. Dial Snap Gage

a common dial snap gage, the adjustable supplementary anvil on the frame provides for centralizing workpieces, and may be used as a bearing in rotating cylindrical work gage roundness. Most dial snap gages have a retracting device that lifts the sensor while positioning the part.

Dial Depth Gage

The dial depth gage as shown in Figure 27-3-10, is similar in construction to the depth micrometer. The dial depth gage improves readability and provides for better precision in repeated measurements. It is typically used for measuring depths of blind holes, recesses and grooves. Dial indicators of extended range permit use of the dial depth gage for a range of depth variations from the master setting.

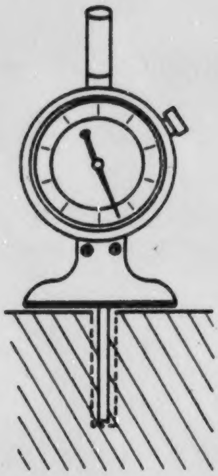
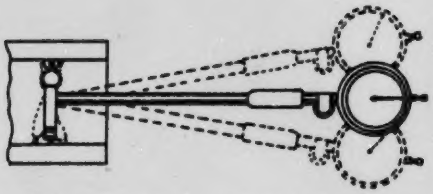


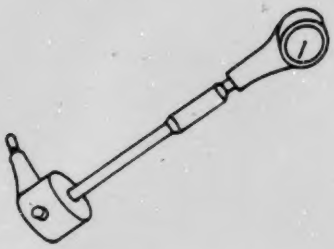
Figure 27-3-10. Dial Depth Gage

Bore Indicator Gage

Bore indicator gages measure internal sizes such as inside diameters of holes and cylinders. Detail (a) of Figure 27-3-11 shows a two point bore indicator gage. With this type of gage, erroneous readings result if the sensors are off the axial plane of the bore or not perpendicular to the bore axis. Centering devices are frequently used to locate the axial plane and rocking of the gage will locate the true bore axis at the minimum reading of the indicator. Detail (b) of Figure 27-3-11 pictures a bore indicator gage with built in centering features. In either type, measurements are possible at various depths and radial positions. Thus, the bore form (roundness and cylindricity) can be determined with the bore indicator gage. However, out-of-roundness due to lobing may be inadvertantly overlooked when using the two point gaging.



(a) Two point bore indicator



(b) Self centering bore indicator

Figure 27-3-11. Bore Indicator Gages

MECHANICAL TEST INDICATORS

Description:

Mechanical test indicators are indicators of special design such that measurement is made of displacement essentially perpendicular to the longitudinal axis of the sensor. A cross-sectional view of a typical test indicator is given in Figure 27-3-12.

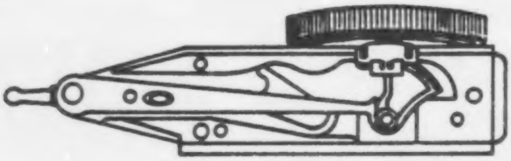


Figure 27-3-12. Cross-Sectional View of Lever and Toothed Segment Test Indicator

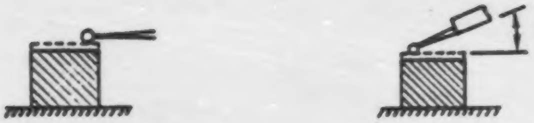
Referring to Figure 27-3-12, the probe (sensor) senses displacement perpendicular to its long axis. Since the probe is not rigidly connected to the hub of the lever in most designs, it can be swiveled to 105° either side of center to establish a desired starting position. Amplification is provided by the internal mechanism consisting of the lever, the two, toothed segments and the two pinions. A flat spring on the lever provides the gaging force. The dial indicator is either parallel as shown in Figure 27-3-12, or perpendicular to the long axis of the instrument.

Test indicators are provided with discrimination of 0.001", 0.0005", 0.0001" and 0.00005" (metric sizes are 0.01mm and 0.001mm). Many test indicators have reversible movement to permit measuring over, under, inside or outside the workpiece.

Accuracy and Precision of Test Indicator

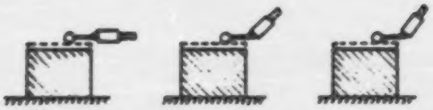
Generally accepted criteria for accuracy and precision of test indicators are equal to that of the dial indicator. That is, accuracy within one increment of the scale and precision within 1/5 increment of the scale are acceptable. Such acceptance criteria apply when the measured displacement is perpendicular to the longitudinal axis of the probe. If measurements are taken at angles away from the perpendicular, cosine error is introduced. While cosine error is often negligible, it is considered when measuring to highly accurate standards. Other sources of error are the same as for dial indicators.

Cosine error is defined as the error introduced by the angle of offset between the probe and the measuring surface. It is caused by the shortening of the effective length from probe tip to the pivot point of the lever. This shorter effective length to the pivot point causes greater lever movement for a given displacement and hence a larger indication of size variation than truly exists. These effects and the formula for calculating cosine error are given in Figure 27-3-13. The measuring errors as illustrated in Figure 27-3-13 are a function of angle Ψ and will increase in an inverse cosine ratio.

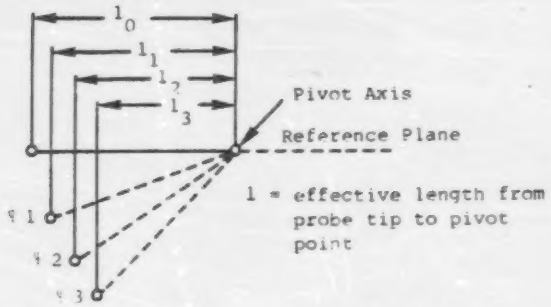


(a) Size Variation Perpendicular to Probe Axis

(b) Size Variation Offset from Perpendicular



(c) Swiveling the Probe to Eliminate Offset


l_0
l_1
l_2
l_3
Pivot Axis
Reference Plane
l = effective length from probe tip to pivot point
ψ 1
ψ 2
ψ 3

(d) Shortening of effective length of probe with increasing (offset angle)

$$E_c = \left(\frac{1}{\text{Cos } \psi} - 1\right) \times 100$$

Where:

E_c = Cosine error in percent of the indicator measurement

ψ = Offset angle

(e) Formula for calculating Cosine Error

Figure 27-3-13. Cosine Error

As shown in detail (c) of Figure 27-3-13, the starting position of the probe can often be swiveled to eliminate an offset angle and, hence, eliminate cosine error. For measurements where space restrictions dictate the use of an offset angle, the operator calculates cosine error and subtracts it from the indicated value to obtain the true reading.

Some manufacturers of test indicators have recently offered specially designed probes which virtually eliminate cosine error. These probes are basically tear-dropped in shape, and they provide an equal but opposite change in effective length when offset due to their unique shapes.

EXAMPLE:

Problem: Is the part acceptable?

Given: A test indicator set to 2.1250" reads -0.0003" with the probe offset equal to 60°. Part tolerance is 2.1250" ± 0.0005".

Solution: Determine cosine error:

$$E_c = \left(\frac{1}{\cos \Psi} - 1\right) 100$$

$$= \left(\frac{1}{\cos 60^\circ} - 1\right) 100$$

$$= \left(\frac{1}{.5} - 1\right) 100$$

$$= 100\%$$

Determine true measurement value:

Standard = 2.1250"

Indicator Reading = -0.0003"

Cosine Error = -0.0003" (E_c x indicator reading)

True Reading = 2.1244"

Conclusion: part is 0.0001" undersize and, therefore, is not acceptable to tolerance.

Applications of Mechanical Test Indicators

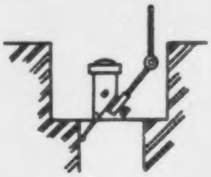
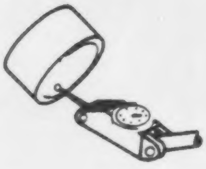
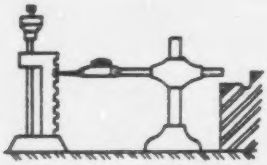
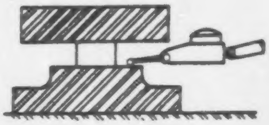
Mechanical test indicators are widely used for comparative measurements where accuracy and precision are very important. The mechanical test indicator is adaptable to comparative measurements on machines and inspection stands. A few of the common applications are illustrated in Table 27-3-7.

ELECTRONIC COMPARATOR INDICATORS

Electronic Measurement

Electronic measurement is the ultimate in precision. With relatively simple instruments the tiniest variation can be detected and amplified for easy reading. Electronic comparator indicators have discrimination as fine as 0.000001 inch or 0.05mm. It is difficult to visualize something as small as one-millionth of an inch, but this example may help. The relationship of one-millionth of an inch to one inch is the same as the relationship of one 25-cent piece to a stack of quarters one mile high.

Table 27-3-7. Common Applications of Mechanical Test Indicators

SKETCH	APPLICATIONS
	1. Distance and form measurements along vertical surfaces. 2. Distance and form measurements in deep lying surfaces and difficult to reach surfaces.
	1. Distance and form measurement of internal surfaces of bores, cylinders, and holes. 2. Centering of rotatable machine tools with respect to datum features.
	1. Transfer of height dimensions to a standard.
	1. Distance and form measurements along horizontal surfaces.

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Description:

The electronic gaging system consists of an electronic amplifier and a gaging head. The gaging head contains a mechanical probe and an electronic transducer such that distance variations are sensed and converted to a proportional electronic signal. The principle of operation to serve this function is based on any one of the following:

- The change in electrical capacitance between two metal plates caused by variations in the distance separating the plates.
- Variation in resistance of wire caused by mechanical strain induced by the sensor.
- The change in self inductance of a coil caused by variations in the position of a movable magnetic body.
- The change in mutual inductance or coupling between coils or transformer caused by variations in the position of a movable magnetic body.
- The voltage produced by bending a piezoelectric crystal by displacement of the sensor.

A common gaging head that employs the fourth principle listed above is the linear variable differential transformer (LVDT). This type of gaging head provides a linear output that also indicates direction of distance variation from the setting standard. This is illustrated by Figure 27-3-14.

The block diagram of Figure 27-3-15 shows an amplifier circuit associated with the LVDT gaging head. The oscillator provides a higher frequency than the 60 hertz line frequency in order to raise the inductive reactance of the transformer windings. The attenuator switch provides for selection of ranges of display. Typical switch settings may be provided

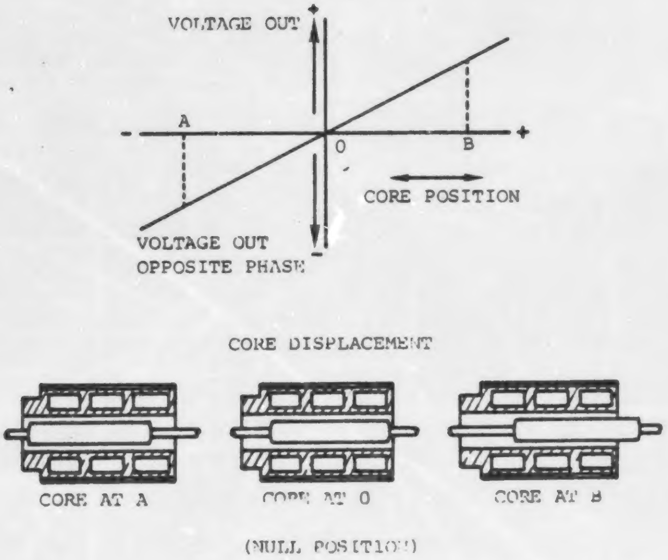
VOLTAGE OUT
+
A
0
B
+
-
CORE POSITION
VOLTAGE OUT
OPPOSITE PHASE
-
CORE DISPLACEMENT
CORE AT A
CORE AT 0
(NULL POSITION)
CORE AT B

Figure 27-3-14. Relative Output of LVDT Gaging Head

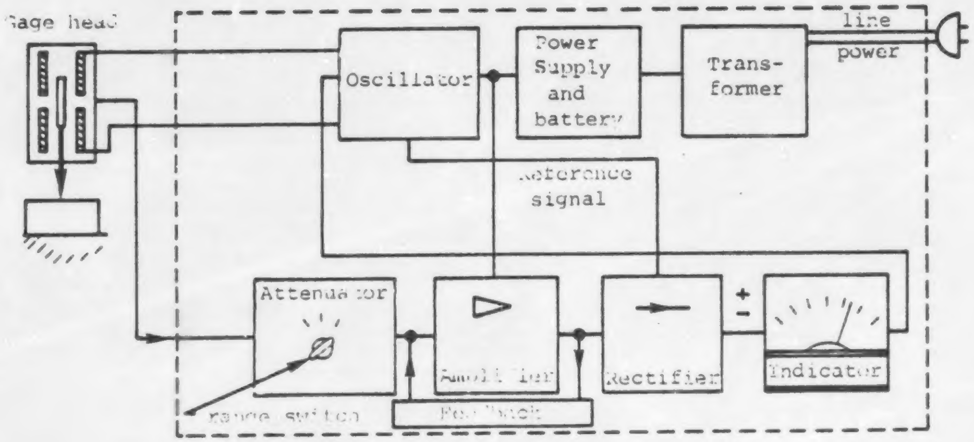
Gage head
Oscillator
Power
Supply
and
battery
Trans-
former
line
power
Reference
signal
Attenuator
Amplifier
Rectifier
+
-
Indicator
Feedback
Range switch

Figure 27-3-15. Block Diagram of Electronic Comparator With LVDT Gaging Head

for discrimination in increments of 0.0001", 0.00005", 0.00001", and 0.000001". (SI units typically have discrimination 0.01mm to 0.05mm.) The amplifier provides high gain linear amplification (e.g., 100,000) that makes it possible to display extremely small changes in output of the gaging head. The indicator provides the readout on scales corresponding to the range selection switch settings. For amplifiers containing plus or minus readout from a mid scale zero point, a zero adjust variable resistor provides for accurate setting of the indicator to zero at the comparative standard set point.

Accuracy and Precision of Electronic Comparator

While the specific design of the gage establishes limits, accuracy and precision of electronic comparators can be substantially better than mechanical indicator comparative gages. In general, the electronic comparator enjoys the following advantages which provide for greater accuracy and precision.

- Extreme Sensitivity - Resolution of the electronic gaging head is considered infinite due to the essentially frictionless movement of the sensor and transducer movable parts and because there are no gears and linkages to provide lag.
- Precise Repeatability - Elimination of gears and linkages removes backlash and intergear play. Electronic gaging heads employ sensor suspension that are almost frictionless.
- Excellent Calibration Accuracy - The electronic circuits provide for accurate adjustment of the zero (standard set point) and the linearity of response throughout the indicator range.

- Very Light Gaging Force - The gaging force used in mechanical indicators for eliminating backlash and play in gears is not necessary for electronic gaging heads. The very light gaging force causes very little wear and strain of the mechanical members.

Each specific type of electronic comparator gage has its own unique accuracy and precision. Extremely accurate and precise electronic comparators are used for measuring reference and transfer gage blocks to determine if such blocks meet the acceptance criteria of ANSI B89.1.9. In such gage block electronic comparators, accuracy of 2% of scale and precision of 1/6 microinch are typical. Thus, if the scale is plus or minus 0.000005 inch, accuracy is plus or minus 0.0000001 inch.

Application

Electronic comparators are used for all applications of mechanical indicators and for measurement of length standards and gage setting masters. In general, electronic comparators are used where feature tolerances are 0.0001 inch and less.

Source of Error

The principal sources of errors of electronic comparators are procedural errors, calibration errors, and drift. Procedural principles of comparative measurement are very important due to the fine sensitivity of electronic comparators. That is, the reference datum and the coincidence of distance variation being measured with the free movement of the probe must be accurately established. Also, flexure in the fixturing must be minimized. Errors of datum or coincidence reflect proportionally in the readout.

Calibration errors are normally these same procedural errors occuring in the calibration laboratory. Drift is a change in the output - input relationship of the electronic amplifier over a period of time. This could be due to the effects of aging of the electronic components and to the combined effects of changes in temperature and humidity. Calibration intervals are established such that recalibration occurs prior to drift introducing significant error.

Certain electronic comparators use a gaging head that senses distance variations that are perpendicular to the axis of the probe (similar to test indicators). An electronic height comparator is an example. For this type of gaging head, cosine error is introduced if the probe is offset from the plane to be measured, unless a self-correcting probe is used.

EXERCISES

The following exercises reinforce the objectives set forth in this module. Answer each question indicated.

1. Gage blocks are physical length standards of known accuracy that provide for the transfer of the basic unit of length to all types of length measurements and serve as measuring devices. Explain three uses.

2. National Standard ANSI B89.1.9 recognizes two styles of gage blocks and establishes four tolerance grades regardless of style. Briefly discuss ANSI B89.1.9.

3. The four tolerance grades are:

   0.1, Ultra Precision
   1 , Laboratory
   2 , Precision

   3 , Inspection

   Briefly discuss their application for a QA/QC Technician.

4. To meet a given tolerance grade, gage blocks must meet the tolerances specified by ANSI B89.1.9 for length, flatness, parallelism, and surface conditions. Discuss why.
5. Material properties desired for materials used in the manufacture of gage blocks are high hardness, excellent homogeneity, and good corrosion resistance. Explain briefly the importance of each of these desired properties.

6. The three basic rules applicable to temperature effects on measurements are as follows. Discuss each rule briefly.

   - Both the measuring device and the item to be inspected must be at the same temperature.

   - Measurements at 68°F do not require correction for thermal effects.

   - Measurement at other than 68°F require calculation of thermal effects to determine if correction is necessary.

7. Thermal effects on measurements can be calculated with the formula $MD = (k_g - k_w)(T - 68°F)$. Give an example.

8. Prior to wringing, gage blocks must be clean and free from burrs. Discuss the reason(s) for this.

9. Are gage blocks wrung together such that the total length is equal to the sum of the individual blocks? Explain.

10. There are five basic rules applicable to wringing of gage blocks. List each of these rules.

11. Measurements with dial indicators, test indicators, and electronic comparators must always be in comparison to an established size (standard). Give two examples.

12. Typical advantages of the mechanical indicator are long measuring range, small size, controlled measuring force, ruggedness, independence of power supply, stability, and economy. List the disadvantages.

13. Dial indicators and test indicators are calibrated for an accuracy of plus or minus ______________ of the dial and for precision of ______ increment of the dial.

14. Electronic comparators are calibrated for an accuracy of ___ of scale and a precision of ____ microinch.

15. Sources of error in measurements with the dial indicators are inherent errors of the dial indicator (clearance in teeth mesh, imperfect gear form, clearance of spindle with its guide, clearance of bearings, and wear) and procedural errors of fixturing and positioning the item to be inspected. Briefly discuss each of these sources of error.

16. Sources of error in measurements with the test indicator are the same as for dial indicators plus ______________ .

17. Sources of error in measurements with electronic comparators are inaccuracies of reference datum and positioning of the item to be inspected, calibration errors, drift, and for certain gaging heads, cosine error. Explain why.

18. Cosine error is calculated with the formula $E_c = \left(\frac{1}{\cos \Psi} - 1\right) 100$ where E_c = ____________________________ ______________________ and Ψ = ______________________.

19. There are five basic principles of operation on which the gaging head for an electronic comparator may be designed. List and briefly explain each of these electronic comparator design considerations.

20. Electronic gage block comparators provide for the inspection of reference and transfer gage blocks to determine their acceptance to tolerance limits of _______________.

MATERIALS

The following materials are required to support this module:

1. Gage Block Set, Grade 2
2. Gage Block Set, Grade 3
3. Dial Indicators with Fixturing of Dial Indicator Gages such as:
   - Dial Bench Comparator
   - Dial Snap Gage
   - Dial Depth Gage
   - Dial Bore Gage
4. Mechanical Test Indicators with Fixturing
5. Adjustable Step-Block Height Transfer Standard
6. Inspection Surface Plate
7. Electronic Comparator (e.g., Gage Block Comparator, Height Comparator, Internal Bench Comparator)
8. Linear Graph Paper
9. Accessories for Surface Plate Inspection (Vee Blocks, Parallels, Tees, e.g.)
10. Thermometers.

PROCEDURES

The following activities reinforce the information presented in this module:

Note to the Instructor:

The instructor should establish laboratory exercises for students/trainees to make measurement using gage blocks, dial indicators, test indicators, and electronic comparators.

The exact exercises will be dependent on the equipment and parts available. Sample exercises are provided below:

1. Cleaning and Deburring Gage Blocks

   NOTE TO INSTRUCTOR: Review with the students/trainees the rules for handling of gage blocks. Demonstrate cleaning and deburring of gage blocks. Then, make assignments for students/trainees to clean gage blocks and examine them for burrs.

2. Building a Combination of Gage Blocks

   (Note: exercises on performing inspections with gage blocks appear later in this module.)

   a. Given: a set of gage blocks
   b. Using Data Table 27-3-1, write the selection of gage blocks for building length standards for the following dimensions:

      1.6505"   2.1552"
      1.3998"   6.5005"

   c. Select gage blocks for one of the combinations of step 2 and wring the blocks to form the length standard. (Caution: ensure gage blocks are clean and free from burrs. Avoid touching measuring surfaces of the blocks. Body fluids contain chlorinated salts which combine with water to form sufficient hydrochloric acid to etch gaging surfaces.)

3. Plot Accuracy of a Continuous Dial Indicator

   a. Given: Dial indicator capable of 2-1/3 revolutions mounted on height stand or bench comparator, set of gage blocks, inspection surface plate, cleaning agent, lint free cloth, linear graph paper.

b. Problem: Plot accuracy of dial indicator readings over two revolutions of the indicator hand as compared to gage blocks.

c. Solution:

   (1) Label the graph paper to show pointer revolutions on the x axis in increments of 1/4 revolution and indicated values on the y axis in increments equal to 1/4 scale of the indicator.

   (2) Plot on the graph paper the straight line that indicates what the dial indicator should read at each 1/4 revolution.

   (CAUTION: Prior to the next step, ensure surface plate and blocks are clean and free of burrs.)

   (3) On a surface plate, set up the dial indicator with gage blocks such that the bezel is zeroed with a slight deflection of the sensor.

   (4) Select and wring gage blocks equal to 1/4 revolution of the dial and sequentially add these to the stack under the sensor until two revolutions of the indicator are made.

   (5) With each incremental stack increase, plot on the graph paper the actual reading of the dial indicator.

   (6) Determine from the plot the maximum error and the linearity of the dial indicator.

4. Height Comparison Measurement

a. Given: Test indicator mounted on a height stand, variable stepped height standard, gage block set, surface plate, cleaning agent, lint free cloth, scratch paper.

b. Problem: Measure the height of a gage block stack to a reference datum

(NOTE: Instructor may substitute a part having a height feature toleranced to a reference datum.)

c. Solution:

(1) Ensure surface plate, gage blocks, part, etc., are clean and free of burrs.

(2) Establish reference datum by placing a parallel block on the surface plate. The top of the parallel becomes the datum. (If a part is provided by the instructor, establish the reference datum in the horizontal plane with appropriate accessories such as vee-blocks, gage blocks, and parallels.)

(3) Place reference datum, test indicator height set, and variable stepped height standard in a triangular pattern and in close proximity such that the test indicator can be shifted from the item being measured to the standard with least practical movement.

(4) Adjust and place test indicator probe on reference datum and set the bezel to zero with slight displacement of the probe. (CAUTION: Swivel probe to eliminate cosine error.)

(5) Twist base of test indicator stand to place the probe on a step of the standard; adjust micrometer head of the standard until test indicator reads zero; record the micrometer value.

(6) Select and wring gage blocks to form a length greater than one step of the height standard. (e.g., if the height standard has one inch steps, select some length above one inch). Record the value selected.

(7) Place the wrung gage blocks on the reference datum (top of parallel).

(8) Twist base of test indicator stand and raise the fixturing to permit placement of probe on top of gage block stack with slight deflection of the probe. Adjust bezel to a zero reading.

(9) Twist base of test indicator stand to place probe on a step of the height standard; adjust micrometer head of the standard until test indicator reads zero; record micrometer reading.

(10) Calculate measured value by subtracting the datum micrometer reading from the measurement micrometer reading and adding the value of steps between the two readings. For example, a micrometer reading of 0.2384 on step 4 and a 0.1634 reading on step 6 of one inch steps would result in:

0.1634	(step 6; measurement reading)
-0.2384	(step 4; datum
-0.0750	(difference)
+2.0000	(value of steps)
1.9250	(value of measurement)

(11) Compare the calculated value of the measurement with the recorded value of the gage block stack. If a difference exists, repeat this exercise until the measurement agrees with the gage block stack. Record probable causes of errors of your measurements.

(12) Optional extensions of this exercise:

- Repeat this exercise with an electronic height comparator. Compare results with those of the test indicator and discuss the relationship of the two measuring devices in terms of ease of use and accuracy.

- Repeat this exercise but with the triangular positioning of the three units greatly enlarged such that the test indicator must be moved a considerable distance from the gage block stack to the height standard. Explain any differences in measurement results (i.e., what affect does the flatness of the surface plate have?)
- Repeat this exercise but with long extension pieces to connect the test indicator with its height stand. Compare differences in results and describe how flexure could have contributed to these differences.

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DATA TABLE 27-3-1. Gage Block Combinations

DIMENSION TO COVER	GAGE BLOCKS SELECTED	DIMENSION TO COVER	GAGE BLOCKS SELECTED
1.6505		2.1552	
1.3998		6.5005	

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REFERENCE MATERIALS

Brown & Sharpe Mfg. Company, Principles and Practice of Precision Measurement, Brown & Sharpe Mfg. Company, Precision Park, North Kingston, R.I., 1975.

Busch, Ted, Fundamentals of Dimensional Metrology, Delmar Publishers, Third Edition, 1966.

Farago, Francis T., PhD., Handbook of Dimensional Measurement, Industrial Press Inc., Third Printing, 1968.

International Business Machines Corp., Precision Measurement in the Metal Working Industry, Syracuse University Press, Syracuse, N.Y., Seventh Printing, 1969.

Society of Manufacturing Engineers (SME), Handbook of Industrial Metrology, Prentice-Hall, Inc., 1967.

American National Standard, ANSI B89.1.9-1973, Precision Inch Gage Blocks for Length Measurement, ASME, New York, N.Y.

International Standard, ISO-1, Standard Reference Temperature for Industrial Length Measurements, ANSI, New York, N.Y.

M.R. Meyerson, T.R. Young, and W.R. Ney, Gage Blocks of Superior Stability: Initial Developments in Materials and Measurement, technical paper, National Bureau of Standards, Washington, D.C.

TEST

Read each question carefully. Be sure to provide the specific information each question requires. Make your answer brief. Use the backs of the test if you need more space.

1. State two purposes of gage blocks.

2. Characterize gage blocks by grade, application, and governing specification by completing the following table for items (a) through (i):

Gage Blocks per ANSI ________ (a)

Tolerance Grade	Common Name	Application
(b)	ultra precision	(c)
(d)	laboratory	(e)
(f)	precision	(g)
(h)	inspection and manufacturing	(i)

3. Name four desirable properties of materials used to manufacturer gage blocks and describe the value of each property in terms of its contribution to accuracy.

Property Contribution

a.

b.

c.

d.

4. Describe why temperature of the measurement must be known if accurate results are to be obtained.

5. Give the following, what is the true value of the measurement; show all calculations:

Measurement Temperature = 90°F
Measured value = 120.450 inches
Thermal expansion coefficients are:
6.5×10^{-6} inch/ inch/°F fir tge gage
9.3×10^{-6} inch/inch/°F for the measured item

6. Given the following set of gage blocks, demonstrate building a gage block length standard equal to 2.2502 inches by listing each block to be used; show all calculations and use the least possible number of blocks:

No. of blocks in Series	Size Range	Increment
9	.1001 to .1009	.0001
49	.101 to .149	.001
19	.050 to .950	.050
4	1.000 to 4.000	1.000

7. Describe the physical conditions which should be met by gage blocks prior to wringing of such blocks.

8. Name five basic rules applicable to wringing of gage blocks.

a.

b.

c.

d.

e.

9. Define Abbe's law and briefly describe how Abbe offset contributes to error of measurement.

10. Define comparative measurement.

11. Name four advantages typically enjoyed by mechanical indicators:

a.

b.

c.

d.

12. Name four sources of error in measurements with dial indicators.

a.

b.

c.

d.

13. Define cosine error.

14. Describe how cosine error can be eliminated.

____
____
____
____

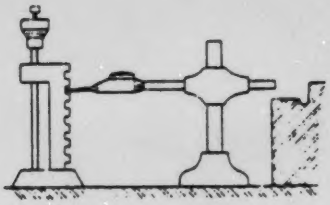
15. Describe how the following sources of error affect the accuracy of measurements with electronic compartments:
a. establishment of reference datum____________
____
____
____
b. drift ____________________________________
____
____
____

16. Describe why comparative measurements are not direct measurements should always be made with dial indicators, test indicators and electronic comparators.

____
____
____
____
____
____

17. Compare the relative accuracies of the dial indicator, test indicator, and electronic comparator.

18. Describe how to measure the height feature in the set-up illustrated below. Include description of reference datum, use of test indicator, use of standard, and method of obtaining the value of the height dimension.



a. reference datum: ______________________________

____

b. use of test indicator: __________________________

____

c. use of standard: ______________________________

____

d. height dimension: _____________________________

____

NUCLEAR TECHNOLOGY

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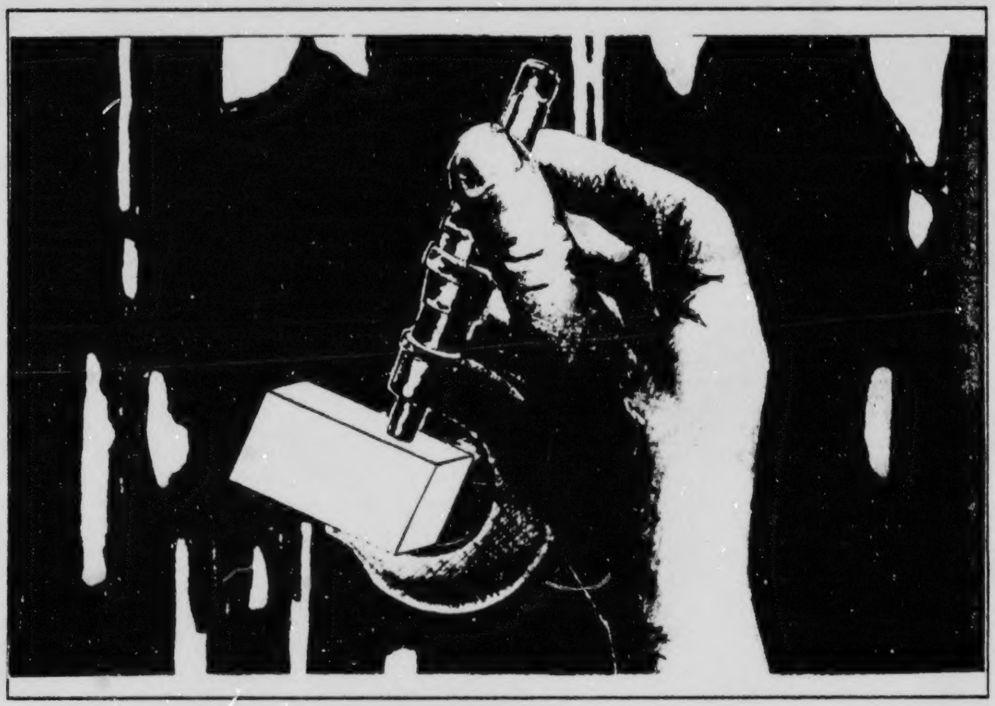
MODULE 27 - 4

ANGLE MEASUREMENT INSTRUMENTS, OPTICAL PROJECTORS AND SURFACE TEXTURE GAGES



COURSE 27: METROLOGY

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 27 METROLOGY

MODULE 27-1	Fundamentals of Metrology
MODULE 27-2	Fixed Gages, Dividers, Calipers and Micrometers
MODULE 27-3	Gage Blocks, Mechanical Comparators and Electronic Comparators
MODULE 27-4	Angle Measurement Instruments, Optical Projectors and Surface Texture Gages
MODULE 27-5	Tolerancing
MODULE 27-6	Calibration
MODULE 27-7	Statistical Techniques in Metrology
MODULE 27-8	The Total Measurement System

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INTRODUCTION

A QA/QC Technician often works with devices which measure angles as well as devices which measure surface texture or smoothness. Many critical dimensions are angular measurements. The surface texture of parts such as bearings and seals are critical to their performance. The QA/QC technicians must not only understand how these dimensions are measured but he must understand the limitations of the measurement devices and the sources of error when they are used.

This module describes the most common devices used to measure angles and surface texture. Specifically, it describes the universal bevel protractor and the sine bar, which are used to measure angles, the engineering microscope and optical projector, which are also used to measure angles but which have several additional uses, and several types of surface texture gages.

MODULE PREREQUISITES

The student/trainee must be familiar with the terms and units of angular measurement. Introductory course work in geometry and trigonometry are useful for this module. The student/trainee also shall have completed all previous modules of this course.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. Describe the following instruments and their general operation: (a) a universal bevel protractor, (b) a sine bar, (c) an engineering microscope and (d) an optical projector.
2. Demonstrate measurement of acute and obtuse angles with (a) a universal bevel protractor, (b) a sine bar, (c) an engineering microscope and (d) an optical projector.
3. Name at least three sources of error in measurements with (a) a universal bevel protractor, (b) a sine bar, (c) an engineering microscope and (d) an optical projector.
4. Demonstrate measurement of distance and form with an optical projector.
5. Define the following surface texture terms: (a) roughness, (b) roughness height, (c) roughness width cutoff, (d) waviness, (e) waviness height and (f) lay.
6. Match surface texture symbols with their application and recognize and interpret data associated with these symbols as given on engineering drawings.
7. Demonstrate measurement of roughness and waviness height.

NOTES TO INSTRUCTOR / STUDENT

The objectives of this module require the student/trainee to demonstrate knowledge of specific instruments and skill in using them. The activities provided involve use of these instruments; however, parts to be measured and the specific instrument to be used must be selected in advance. Parts selected should possess (1) acute and obtuse angles, (2) inside and outside lengths, (3) surfaces with toleranced surface texture and (4) for the optical projector, geometric forms of parallelism and perpendicularity. Screw threads are suggested for use with the optical projector.

Because this module makes reference to basic geometric and trigonometric concepts. It would be useful for the instructor to review the basic concepts of angular measure, types of angles, Pythagorean Theorem and the sine, cosine and tangent functions employed in trigonometry.

SUBJECT MATTER

ANGLE MEASUREMENT

Units

Most hardware industries in the United States use the sexagesimal system for designating angular relationships of mechanical features. The basic unit is the degree (°), where a full circle has 360° and a right angle, 90°. Each degree is divided into 60 seconds (') (1° = 60') and each second is divided into 60 minutes (") (1' = 60"). When angles are measured in radians, a full circle has 2π radians and a right angle has $\frac{\pi}{2}$ radians. The relationship between degrees and radians is 1 radian = 57.296° and $1° = \frac{\pi}{180}$ radians.

Types of Angle Measurement Devices

Devices used to measure angular relationships generally fall into the categories of (1) fixed gages, (2) protractors, (3) indexing tables and (4) optical devices. Fixed gages, such as taper plugs and ring gages are used to measure angles. Angular gage blocks can be used to measure angles up to 90°. Protractors range from simple semicircles with degree marks to more elaborate devices such as the universal bevel protractor. A wide variety of indexing tables are used in machining angular features. They can also be used for measuring angular relationships, either integral with machines or as separate devices. Indexing tables are available with one, two or three indexing coordinates. Optical devices used to measure angles include the engineering microscope and the optical projector.

UNIVERSAL BEVEL PROTRACTOR

Description

The universal bevel protractor, shown in Figure 27-4-1, employs precision straight edges in direct contact with the physical boundaries of the angle being measured. The sliding blade is fixed to a reference point of the primary circular scale such that its straight edge forms a tangent to the reference point. It can be slid along its longitudinal axis to offer various lengths of tangential straight edge. The non-sliding blade rotates about the center of the primary scale. The vernier scale is fixed to the hub of the rotating blade and provides the point of readout. The auxiliary blade assists in the measurement of acute angles. In most designs, the detachable auxiliary blade can be positioned parallel to or at right angles to the rotatable blade. Figure 27-4-2 illustrates typical measurements using a universal bevel protractor.

Reading the Scale

The 360° scale of the universal bevel protractor is graduated in one degree increments and divided into four 90° quadrants. From the reference point of the sliding straight edge, the scale progresses in either direction from 0 to 90° and back to 0° at the point 180° from the initial zero. The vernier scale is graduated in five minute increments with twelve increments to each side of zero. The zero on the vernier scale is the starting point for determining the readout. The increments on the vernier provide discrimination of 5'.

The basic principles of reading the scale of a universal bevel protractor is illustrated by the simplified sketch in Figure 27-4-3. The sketch shows a line tangential to the reference 0° point of the primary scale. When the

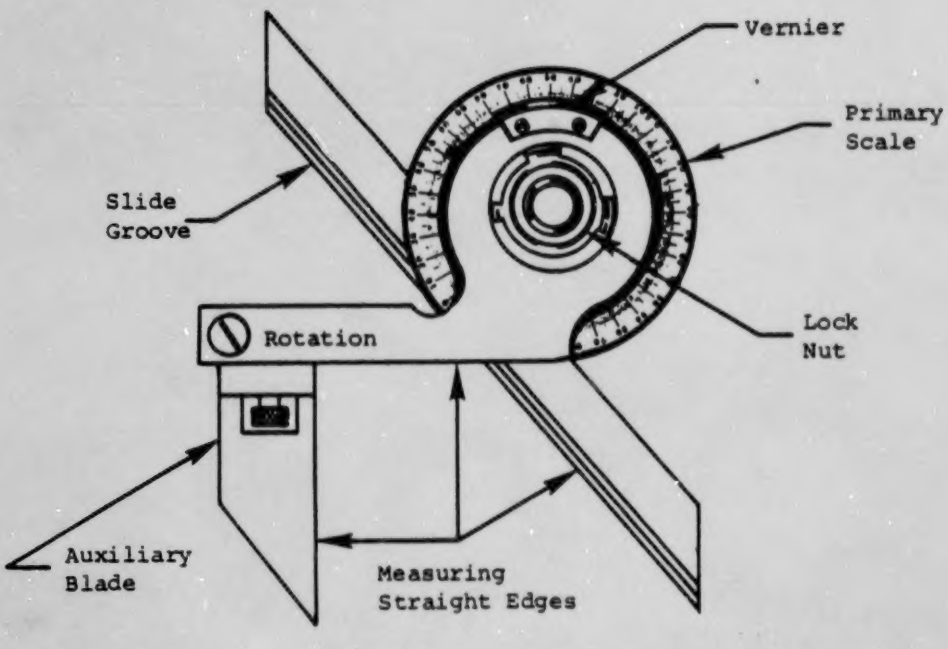

Vernier
Primary Scale
Slide Groove
Rotation
Lock Nut
Auxiliary Blade
Measuring Straight Edges

Figure 27-4-1 Universal Bevel Protractor

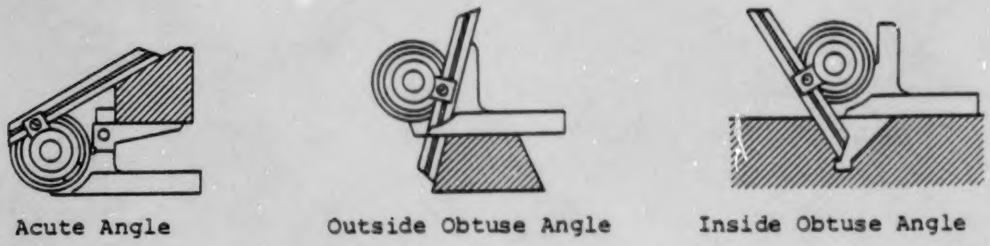

Acute Angle
Outside Obtuse Angle
Inside Obtuse Angle

Figure 27-4-2 Measurements Using Universal Bevel Protractor

rotatable line forms a right angle with the tangential line, the hub arrow is scribed to read 90°. The arrow represents the zero of the vernier scale of an actual bevel protractor. As the rotatable line is rotated, the fixed arrow will read either the angle measured or the supplement of the angle measured.

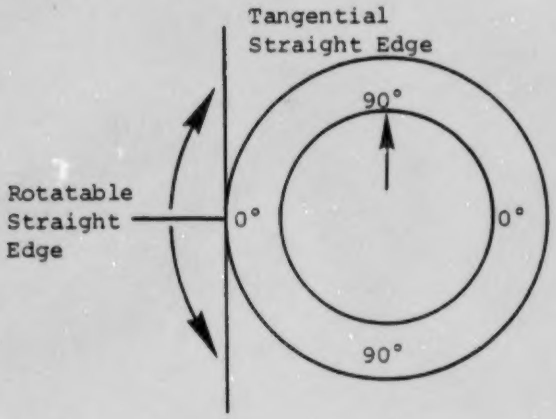
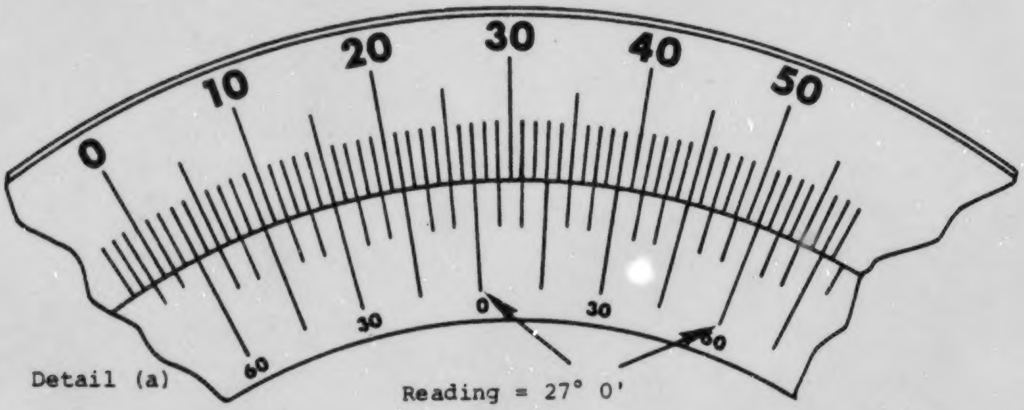


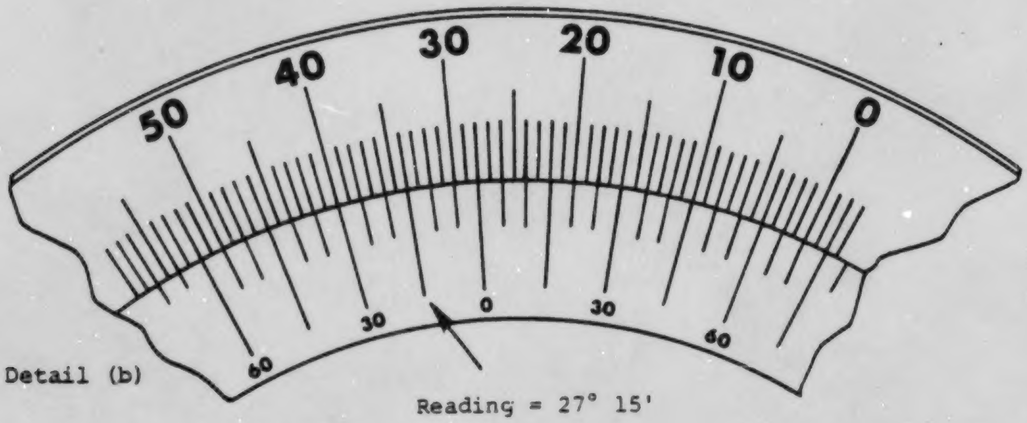
Figure 27-4-3 Reading the Scale of a Universal Bevel Protractor

Figure 27-4-4 shows how readings are obtained. The zero of the vernier identifies the whole degrees as read from the primary scale at the vernier zero. Minutes are read on the vernier in the same direction from zero as the vernier moved from zero of the primary scale. In the first example shown in Figure 27-4-4, the vernier zero indicates 27 degrees. Visual inspection of the vernier scale to the right (same direction as from zero of the primary scale) identifies that the coincident line of the vernier with the primary scale is 60 minutes. Therefore, the reading is exactly 27 degrees, or, 27° 0'. In the second example shown in Figure 27-4-4, the vernier zero indicates 27 degrees. In this case, the lefthand vernier scale coincides with the primary scale 15'. Therefore, the reading is 27 15'. In actual measurements, one must be observant of whether the direct reading is the measured angle or its supplement. For supplements, the reading is subtracted from 180°.


0
10
20
30
40
50
60
30
0
30
60

Detail (a)

Reading = 27° 0'


50
40
30
20
10
0
60
30
0
30
60

Detail (b)

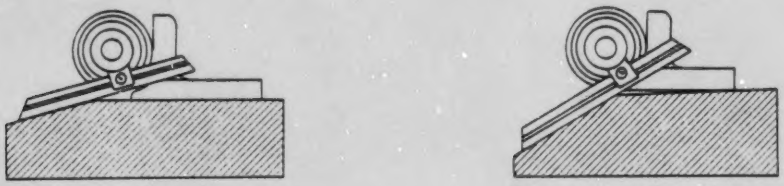
Reading = 27° 15'

Figure 27-4-4(a) and (b) Reading the Vernier of a Universal Bevel Protractor

Accuracy and Error Sources

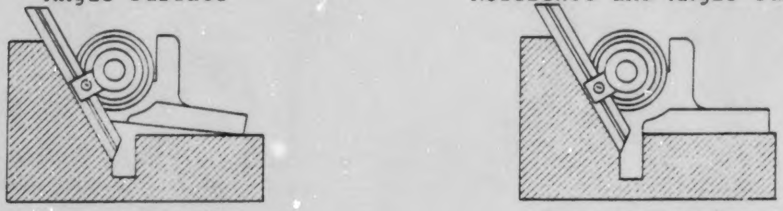
The accuracy of measurements with a universal bevel protractor depends on the inherent accuracy of the instrument which is best determined by calibration. Inherent features affecting accuracy are the straightness of the edges of the blades, the bearing accuracy of the rotatable blade, and the scale accuracy.

With respect to procedural errors using a universal bevel protractor, the most common are manipulative errors, readout errors, and lack of cleanliness of bearing surfaces. Manipulative errors result in a misalignment of blade straight edges with the boundaries of the angle. Readout errors stem from incorrect reading of the vernier and incorrect calculations. Foreign materials or burrs on the surfaces of the angle boundaries cause a misalignment of straight edges with such boundaries. Figure 27-4-5 illustrates misalignments that are caused by either manipulative errors, foreign materials, or burrs.



Incorrect Bearing on Angle Surface

Incorrect Bearing on Reference and Angle Surface



Incorrect Bearing on Reference Surface

Correct Bearing

Figure 27-4-5 Alignment of Universal Bearing Protractor Straight Edges

SINE BAR

Description

The sine bar is a hardened, stabilized, precision ground and lapped tool for accurate angle measurement. It consists of a flat bar to which two cylinders of equal diameter are attached at a known separation. When the cylinders are brought in contact with a flat surface, the top of the bar is parallel to that surface. Starting from this position, if a block of known height is placed under one of the cylinders, the angle by which the top surface of the bar becomes tilted can be calculated. The flat working surface can also be a block or plate. Hence, this class of tool includes sine bar, sine block, and sine plate. Figure 27-4-6 shows a sine bar with its case.

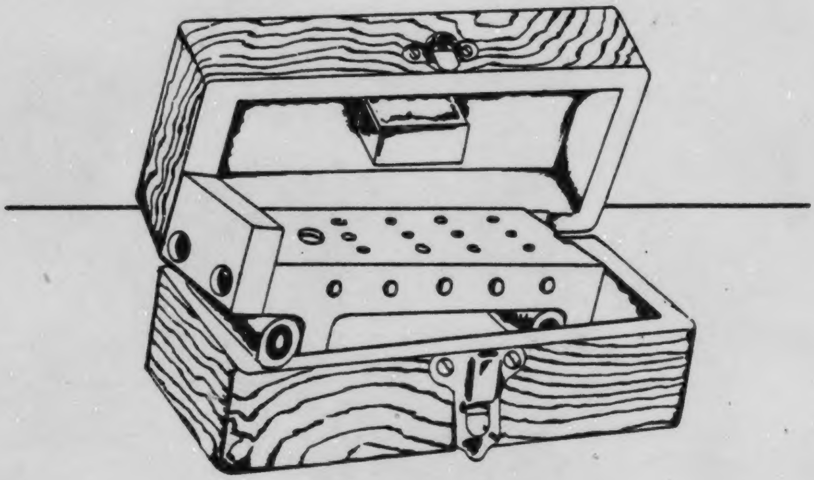
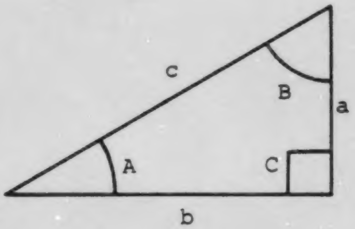


Figure 27-4-6 Sine Bar with Case

Sine bars are suitable for measuring angular features of relatively small parts when either tolerance or access limitations make the universal bevel protractor unsuitable. In general, a sine bar is more suitable than a universal bevel protractor when angles are toleranced in minutes.

Principles of Use

Sine bars measure angles by using basic trigonometric functions of a right triangle. These basic functions are shown in Figure 27-4-7. If two sides or one side and one angle of a right triangle are known, the remaining variables can be determined. Table 27-4-1 shows the calculations required.



a = Altitude
b = Base
c = Hypotenuse

$\angle A = 90° - \angle B$
$\angle B = 90° - \angle A$
$\angle C = 90°$

$$a^2 + b^2 = c^2$$

$\sin A = \frac{a}{c}$ $\quad$ $\sin B = \frac{b}{c}$
$\cos A = \frac{b}{c}$ $\quad$ $\cos B = \frac{a}{c}$
$\tan A = \frac{a}{b}$ $\quad$ $\tan B = \frac{b}{a}$

Figure 27-4-7 Basic Trigonometric Functions

Table 27-4-1 Basic Trigonometric Calculations

Known	Calculation
Two Sides	Determine the third side using $a^2+b^2=c^2$; determine the angles using trigonometric functions.
One Side and One Angle	Determine the other angle by subtraction; determine the second side using a trigonometric function; determine the third side using $a^2+b^2=c^2$.

A sine bar consists of two equal-sized, hardened, and precision ground cylinders attached to a straight, rectangular bar. The axes of the cylinders are parallel to the working surface of the bar, and the center distance between the two cylinders is a fixed dimension. The sine bar serves as a constant hypotenuse of a length equal to the center-to-center distance of the two cylinders. This known length is 5, 10, or 20 inches dependent on the particular size of the sine bar.

As shown in Figure 27-4-8, the sine bar serves as a reference plane at a known angle. The angle at which the sine bar is placed is calculated using Equation 27-4-1. When inspecting parts, the angle and its tolerance are specified by drawings of the part. With the nominal angle thus known, the gage block height required to set the sine bar is calculated using Equation 27-4-2.

$$\sin \theta = \frac{h}{c} \qquad \text{(Eq. 27-4-1)}$$

$$h = c \sin \theta \qquad \text{(Eq. 27-4-2)}$$

Where

θ = sine bar angle
h = height of gage blocks
c = standard length of the sine bar

In determining the gage block height, attention must be given to the reference plane established on the sine bar in relation to the part feature. Figure 27-4-9 shows three methods for mounting a part on a sine bar and how these methods affect the angle being measured.

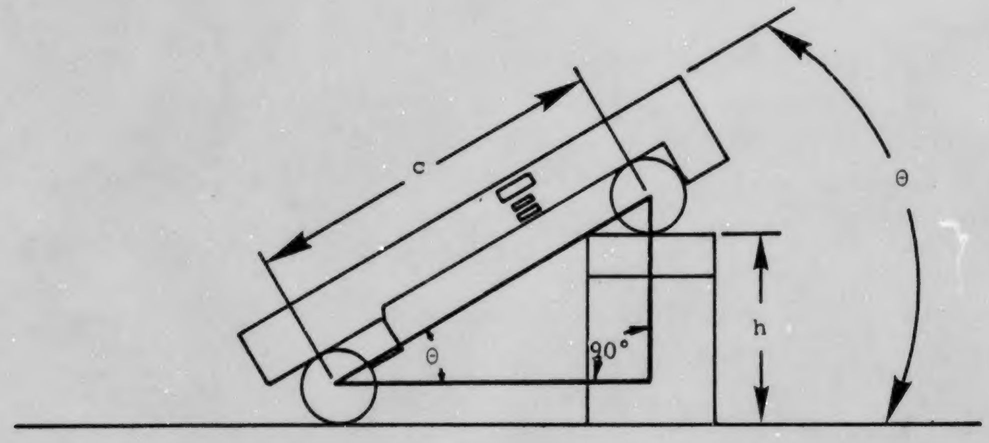
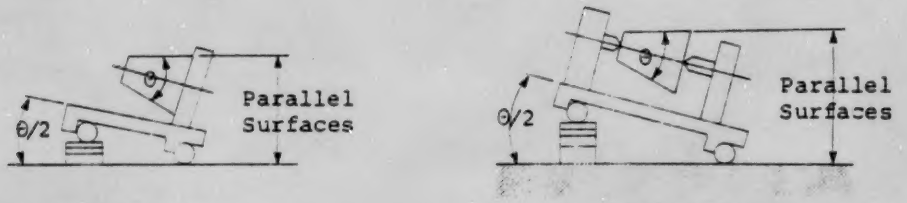
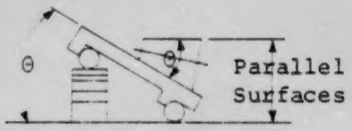


Figure 27-4-8 Sine Bar Relationships


Θ/2
Θ
Parallel Surfaces
Θ/2
Θ
Parallel Surfaces

Face Based

Axis Based


Θ
Θ
Parallel Surfaces

Side Based

Figure 27-4-9 Sine Bar Mounting Methods

With a part mounted by one of the methods shown in Figure 27-4-9, a height indicator is used to measure the height variation along the angle surface that is nominally parallel to the reference plane. Any height variation indicates angular deviation from the nominal angle. The height to angle deviation relationship is calculated using Equation 27-4-3.

$$\tan \phi = \frac{i}{\ell} \qquad \text{(Eq. 27-4-3)}$$

Where

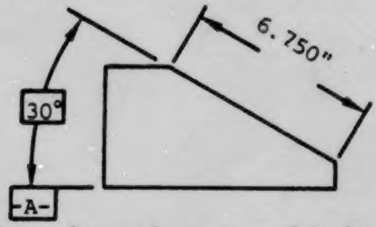
ϕ = angular deviation

i = indicated height variation

ℓ = length of surface explored to obtain the height variation

EXAMPLE

Problem: Using a ten inch sine bar, show the calculations associated with measuring the angle of the following part.



Given: Sine bar length = c = 10 in.
Part angle = θ = 30°
Height variation = i = 0.015 in.
Length of exploration = ℓ = 6.750 in.

Solution: Determine gage block stack height.

$h = c \text{ sine } \theta$

$h = (10 \text{ in.})(\sin 30°)$

$h = (10 \text{ in.})(0.5)$

$h = 5 \text{ in.}$

Mount datum A on measuring surface of sine bar; place 5 inch gage block (or a 4" and 1" wrung into a stack) on surface plate and under one cylinder of the sine bar.

Using a test indicator height set, explore the surface of the angular feature to determine height variation.

Calculate the angular deviation:

$$\tan \Theta = \frac{i}{\ell}$$

$$\tan \Theta = \frac{0.015 \text{ in.}}{6.750 \text{ in.}}$$

$$\tan \Theta = 0.0022$$

$$\Theta = 0.127° (0° 7.64') (0° 7' 38")$$

If the angle were bilaterally toleranced (e.g., ± x°), an acceptance decision is made without regard to the direction of the angular deviation. However, if limit or unilateral tolerancing applies (e.g., 30° maximum or $30° \pm \frac{0}{x°}$) the direction of angular deviation must be determined. If the angular surface is explored from the vertex end, a negative height deviation indicates a decreasing angle while a positive height deviation indicates an increasing angle.

Accuracy and Error Sources

Sine bars are provided with inherent accuracy of about 10 seconds of arc for commercial grades and about 5 seconds of arc for laboratory grades. Sine bar features which determine the inherent accuracy are flatness and squareness of the working surface, roundness and straightness of cylinders, parallelism of cylinders with each other and the working surface, and accuracy of the center distance between cylinders.

Accuracy of sine bar measurements is less than the inherent accuracy of the sine bar. Error sources include misalignment in the mounting of parts which introduces cosine errors, precision of measuring the gaging distance of the surface explored by the height gage, errors of the height gage, flatness of the surface plate, and calculation errors.

ENGINEERING MICROSCOPES

Description

Engineering microscopes are optically assisted instruments for measuring lengths, angles and geometric forms. The microscope permits observation of part features coincident with the optical axis of the instrument. Measurement of features is obtained by measuring the displacement of the part necessary for optical alignment with the boundaries of the feature being measured. Such measurement is by micrometer lead screws or with graduated scales within the field of view or a combination of these.

Most engineering microscopes employ collimated light passing by the object being measured to the microscope. In this manner a silhouette of the object is viewed. For observation of recesses where silhouetting is impossible, the reflection of light from the object permits measurement. The basic parts of a common silhouetting engineering microscope are shown in Figure 27-4-10.

A typical measuring instrument employing an engineering microscope is shown in Figure 27-4-11. The precision table of this instrument serves as a reference plane. It is adjustable in two coordinates by micrometer lead screws. An optical protractor located within the gratical chamber permits measurement of angles. Both silhouetting and reflecting light sources are included.

The universal measuring microscope shown in Figure 27-4-11 has eyepieces and objective lenses which provide the amount of magnification required. The graticle has precisely aligned cross hairs, and the

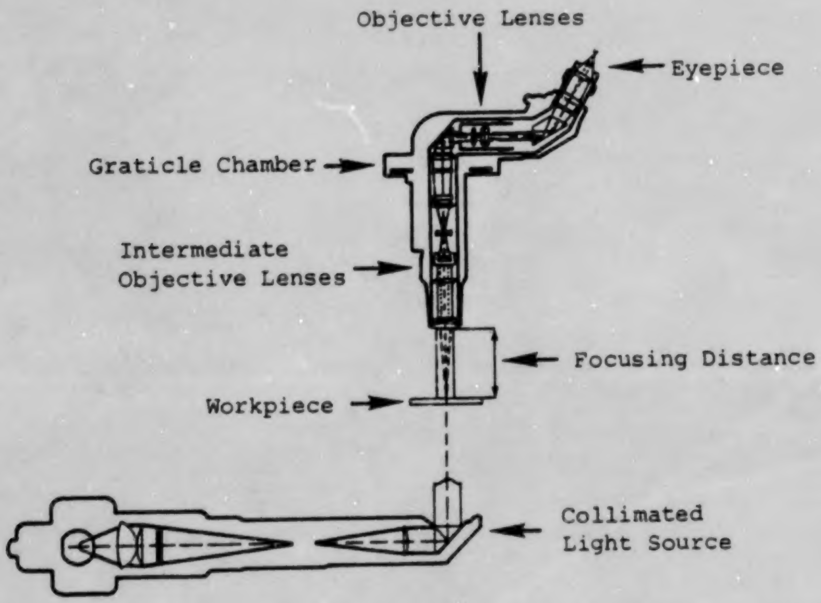

Objective Lenses
Eyepiece
Graticle Chamber
Intermediate Objective Lenses
Focusing Distance
Workpiece
Collimated Light Source

Figure 27-4-10 Engineering Microscope

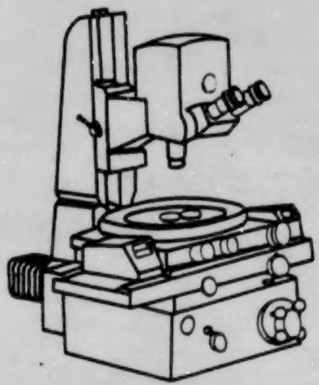


Figure 27-4-11 Universal Measuring Microscope

protractor rotates the graticle to position the cross hairs for angular measurement. The two micrometer heads permit 1" movement of the stage in either direction and are graduated for readings to 0.0001". A typical view of optical protractors is given in Figure 27-4-12. The master scale of 360° is superimposed on a readout scale graduated in minutes. One boundary of the silhouette is aligned with a

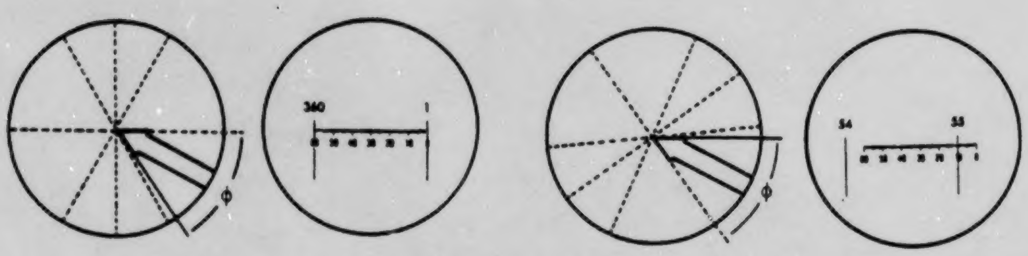


Figure 27-4-12 Angle Measurement with an Optical Protractor

cross hair at a reading of 0°. The other boundary is aligned with a cross hair showing a reading of 54°10'. The difference between these two readings is the angle formed by the object being measured. The initial setting is of no consequence since the difference between the two readings equals the measurement.

Engineering microscopes can also be used to make linear measurements. The workpiece is placed on the stage and aligned with the cross hairs. Using the micrometer heads, the reference point on the work is brought under the cross hair and a reading taken. The work is then moved with the micrometer to bring the point being measured under the same cross hair. A second reading is taken, and the difference is the measurement.

Accuracy and Error Sources

Accuracy of angular measurements with the optical protractor can be as much as plus or minus 30 seconds. For those containing a vernier, accuracy can be as much as plus or minus 10 seconds. Aside from the excellent accuracy and precision of the instrument itself, procedural errors typically include part misalignment, reading errors and calculation errors.

OPTICAL PROJECTORS

Description

Optical projectors are optically assisted instruments for measuring lengths, angles and geometric forms by projection of an image of the object being measured on a screen. Figure 27-4-13 is a simplified schematic showing the basic operation of an optical projector.

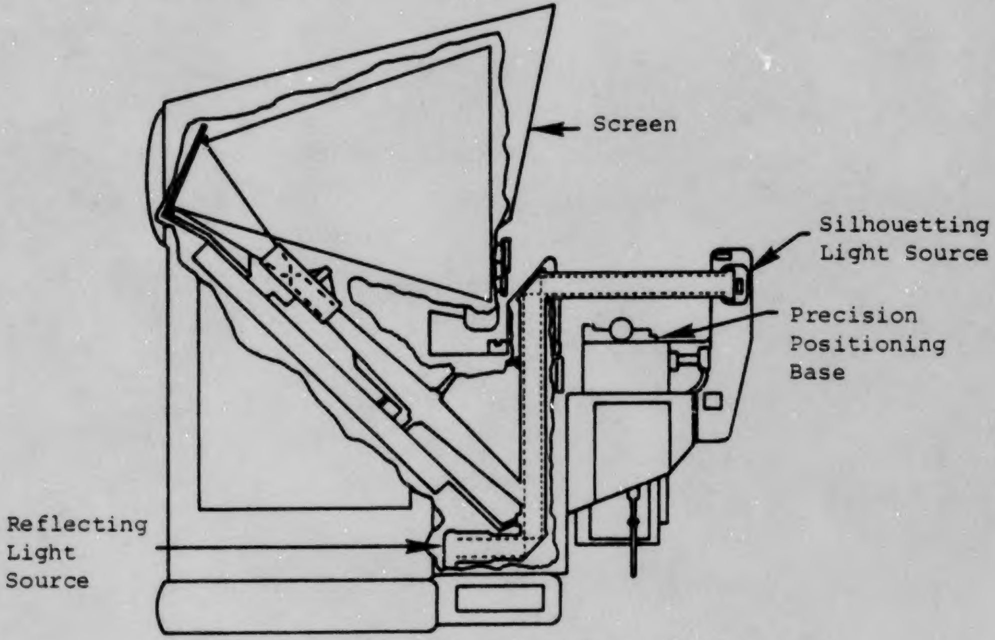


Figure 27-4-13 Optical Projector

For precision measurement, the optical system must project images which are clear, sharp, and dimensionally accurate. The mechanical design and function of the projector must also be compatible with the precision of the optical system. The design must provide ample working space for the positioning of parts. The viewing screen, on which the image is formed, must be located in a position convenient to the operator at normal eye level. Operating controls must be convenient and accessible.

To satisfy these requirements, all optical projectors incorporate in their design several essential features.

- Light Source - High intensity lamps of 1000 watts or more are typically used. Reflecting mirrors project a light beam to collimating lenses. The optical projector in Figure 27-4-13 has two light sources that can be selected. The silhouetting light projects an outline of the part; the reflecting light from the part is projected on the screen.
- Condenser or Collimating Lens System - This system provides for sharp images on the screen by eliminating all but parallel rays of light.
- Workpiece Positioning Table - The part is staged on the table to present the contour or reflecting surface to be viewed on the screen. The optical projector in Figure 27-4-13 has a micrometer lead screw to position the table which provides for precision positioning of the part.
- Mirrors and Lenses - High resolution lenses and highly reflecting mirrors are used to provide a clear, sharp, and magnified image on the screen. The lens and mirror system is designed to give an upright and unreversed image.
- Viewing Screen - Screens are made with fine textured ground glass to provide a glarefree image without localized areas of brilliance. Also, the screen should not introduce distortion of the image or be so bright as to cause eye fatigue.
- Chart-Gages - The effective use of all optical projectors relies upon a chart-gage. It furnishes the point of reference for the operator

when making measurements. Some projectors are furnished with ground glass viewing screens without markings of any kind. They are intended simply as a surface on which an image can be formed. Before any measurements can be made of the image, however, a chart-gage with reference lines must be mounted over the screen. Most projectors, however, are equipped with viewing screens which are also chart-gages. They usually have horizontal and vertical centerlines only, although many also include one or two angular lines as well. Chart-gages of this type provide a positive index of reference lines from which measurements can be taken. Chart-gages are also available in many styles, generally being specially designed for a specific part. Most chart-gages are processed on glass or plastic. They are classified in three types: (1) replacement chart-gages, (2) overscreen chart-gages, and (3) overlay chart-gages.

The first basic use of an optical projector is for so-called toolroom applications and single-piece inspections. Such a projector requires precision in the staging table mechanism and in the measuring devices associated with it. Since measurements are made with reference to a cross line on the center of the projector screen, just as in a toolmaker's microscope, there is no prime requirement for a completely accurate image over the entire screen. A clear, well-defined image will suffice. Movement of the positioning table to place first one boundary of the feature on the cross line and then to place the other boundary on the cross line gives a measurement by the difference in micrometer settings at the two boundaries.

The second basic use of an optical projector is for comparison measurement. In this use, the projected image of the part is compared with an enlarged layout placed directly on the screen. The overlay may be spread over the entire screen area and it must correspond with the magnification setting of the projector. In such applications, accuracy of the image in all areas of the screen is very important. Thus, for toolroom applications prime emphasis is placed on mechanical measuring, while for comparison applications prime emphasis is placed on the accuracy of the optical system.

Since in most industrial plants, projectors are frequently used for both types of inspections, it is generally accepted that equipment must have both a precise optical system and means for precise mechanical measuring.

Principles of Use

There are three basic techniques for measurement generally employed in optical projector usage: (1) measurement by comparison, (2) measurement by movement and (3) measurement by translation.

The inspections performed on many parts are concerned not so much with actual part dimensions as to whether the parts are within permissible tolerance limits. These are essentially go, not-go inspections made by comparison to a master. A chart-gage identifying limits of length, angle, or form serves as the master.

Analytical inspections are concerned generally with the dimensions themselves. It is necessary to make careful measurements of each of the dimensions, and this is usually a slower operation than that which compares a part to a master. Regardless of the type of chart-gage used, precision movement of the part (and/or the protractor for angular measurements) is required for accurate measurement of specific lengths, angles or form features.

A great many parts contain features that cannot be projected by a light beam directly but whose contours can be measured indirectly by translation. This is accomplished by a combination of tracing and optical projections.

All optical projectors are suitable, within the capability of the optical and mechanical design, for making measurements by comparison. To measure by movement requires a projector with table travel and appropriate measuring devices. Measurement by translation requires special tracer accessories.

The optical projector equipped with optical protractor rings provides the means for making accurate readings of angular values on projectors. The rotational feature also serves as a useful tool in some inspection procedures not directly concerned with angular measurement. Protractors must be as carefully designed and machined as any other part of the projector.

Protractors are standard equipment on most measuring projectors and are available as auxiliary equipment on many others. The rings serve as the holder for the viewing screen. Adjustments are provided in most projectors for exactly centering the screen in the ring although one manufacturer machines rings and glass to avoid this operation. Once assembled, both the protractor ring and the screen should be concentric with the optical axis of the projector.

Degrees of arc are usually marked directly on the rings. Readings are made with correlated verniers having scales readable to one minute of arc. Some of the rings used on very large projectors are marked for every 10° and are used with a continuous-reading dial vernier from which the intermediate degrees and minutes can be read. These vernier dials are readable to one minute of arc also.

To measure angles, the part datum is aligned to a radial datum on the chart-gage such that the vertex is at the center point. Rotation of the chart-gage to align the radial datum with the angle silhouette provides a readout on the protractor.

SURFACE TEXTURE MEASUREMENT

Definitions

The national standard for surface texture is ASA B46.1 sponsored by the American Society of Mechanical Engineers. At the time of this writing, the 1962 revision of B46.1 is undergoing review by a National Standards Committee (B-89). Because possible revisions that may be made are unknown, this section is based on ASA B46.1 - 1962.

Surface texture of many surfaces of parts are important to the function of the part. In particular, mating surfaces are frequently required to perform as bearing or sealing surfaces. The required texture of such surfaces are stipulated on engineering drawings. In this regard, surface texture designations pertain to roughness, waviness and lay.

A number of unique terms are used in the specification of surface texture requirements and the inspection of surfaces for compliance with specified requirements. The student/trainee should memorize the definition of these terms. Figure 27-4-14 illustrates these terms.

- Surface Texture - The repetitive or random deviations from the nominal surface which form the pattern of the surface is called surface texture. Surface texture includes roughness, waviness, lay, and flaws.

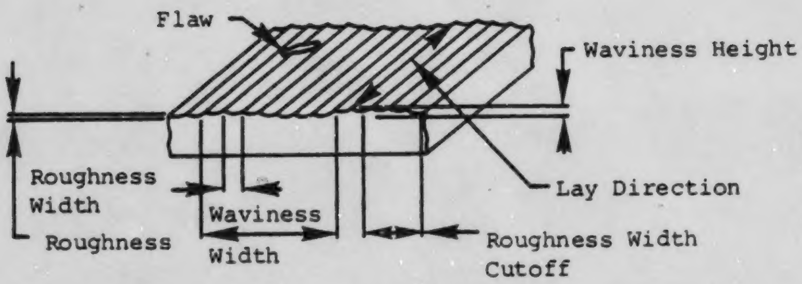


Figure 27-4-14 Surface Texture Terms

- Roughness - Roughness consists of the finer irregularities in the surface texture, usually including those irregularities which result from the inherent action of the production process. These are considered to include traverse feed marks and other irregularities within the limits of the roughness-width cutoff.
- Roughness Height - The arithmetical average deviation expressed in microinches measured normal to the center line is called roughness height.
- Roughness Width - The distance parallel to the nominal surface between successive peaks or ridges which constitute the predominant pattern of the roughness is called roughness width. Roughness width is rated in inches.
- Roughness-Width Cutoff - The greatest spacing of repetitive surface irregularities to be included in the measurement of average roughness height is called the roughness-width cutoff. Roughness-width cutoff is rated in inches. Roughness-width cutoff is always a function of the measuring instrument and it must always be greater than the roughness width in order to

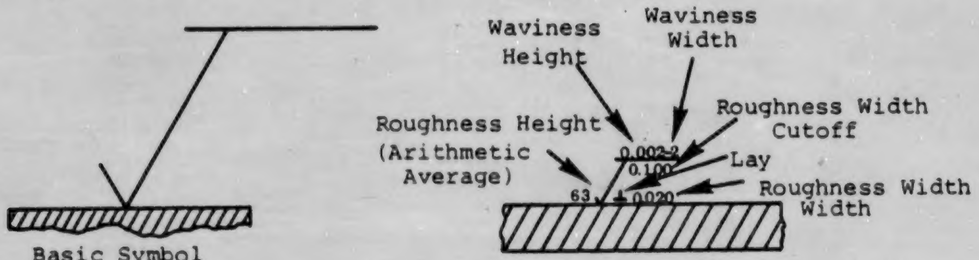
obtain the total roughness height rating. Standard tables list roughness-width cutoff values of 0.003 in., 0.030 in., 0.100 in., 0.300 in. and 1.000 in. When no value is specified, the value of 0.030 in. is assumed.

- Waviness - The widely spaced component of surface texture of generally wider spacing than the roughness-width cutoff is called waviness. Roughness may be considered as superimposed on waviness.
- Waviness Height - The peak-to-valley distance of waviness rated in inches is called waviness height.
- Waviness Width - The spacing of successive wave peaks or successive wave valleys rated in inches is called waviness width. When specified, the values shall be the maximum permissible.
- Lay - The direction of the predominant surface pattern, ordinarily determined by the production method used is called lay.
- Flaws - Irregularities which occur at one place or at relatively infrequent or widely varying intervals in a surface are called flaws. Flaws include such defects as cracks, blow holes, checks, ridges, scratches, etc. Unless otherwise specified, the effect of flaws are not included in the roughness height measurement.
- Profile - The contour of a surface in a plane perpendicular to the surface unless another angle is specified is called profile. Profile is defined to distinguish between surface texture and profile. As described later, some

profiling systems are adaptable to measurement of surface texture.

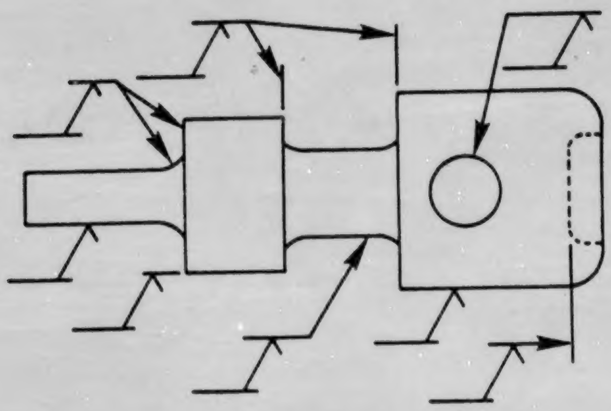
Symbols

All requirements pertaining to surface texture are contained in the surface texture symbol and its associated data. The symbol, the surface to which it applies and the placement of associated data are illustrated in Figure 27-4-15.


Waviness Height
Waviness Width
Roughness Width Cutoff
Roughness Height (Arithmetic Average)
0.002-2
0.100
Lay
63
0.020
Roughness Width Width

Basic Symbol

Data Placement



Applications of Symbol to Surface

Figure 27-4-15 Surface Texture Symbols

As illustrated in Figure 27-4-15, the basic surface texture symbol is the check mark with a horizontal extension. Figure 27-4-15 also shows the location of values that are shown by drawings for each of the terms applicable to surface texture. Except for roughness-width cutoff, all values specified by the drawing are maximum values. For the part to be acceptable, measured values must be equal to or less than the maximum specified. In addition to the maximum roughness height, a minimum roughness height may be specified immediately above the maximum value. The value of the roughness width cutoff is used in the measurement procedures. Where a value is not specified by the drawing, 0.030 in. is used.

When specified by the drawing, lay symbols dictate to manufacturing the method of finishing the surface. Inspection of surface texture determines that the finished surface complies with the drawing requirement. Standard lay symbols and their meaning are listed in Table 27-4-2.

Surface Texture Production

Different manufacturing processes commonly result in different surface textures. Table 27-4-3 shows a comparison of roughness height for several manufacturing processes.

SURFACE TEXTURE STYLUS SYSTEM

Description

By far the most common way to measure surface texture is by the movement of a stylus over the surface and the measurement of an electrical signal produced by a transducer attached to the stylus. Such instruments have meter or chart readout or both. While a wide variety of instruments are available with each having its own unique features, all instruments have in common a stylus, transducer, drive mechanism, amplifier and readout. These are illustrated in Figure 27-4-16.

Table 27-4-2 Lay Symbols

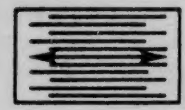
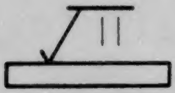
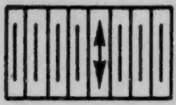
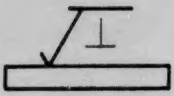
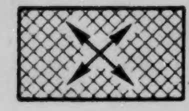
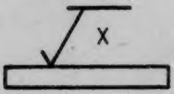
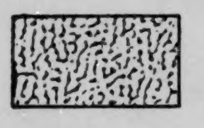
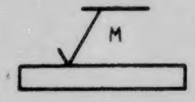
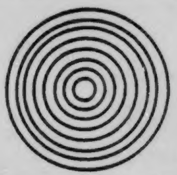
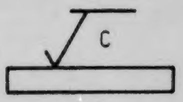
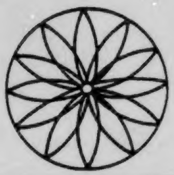
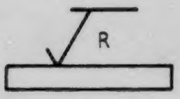
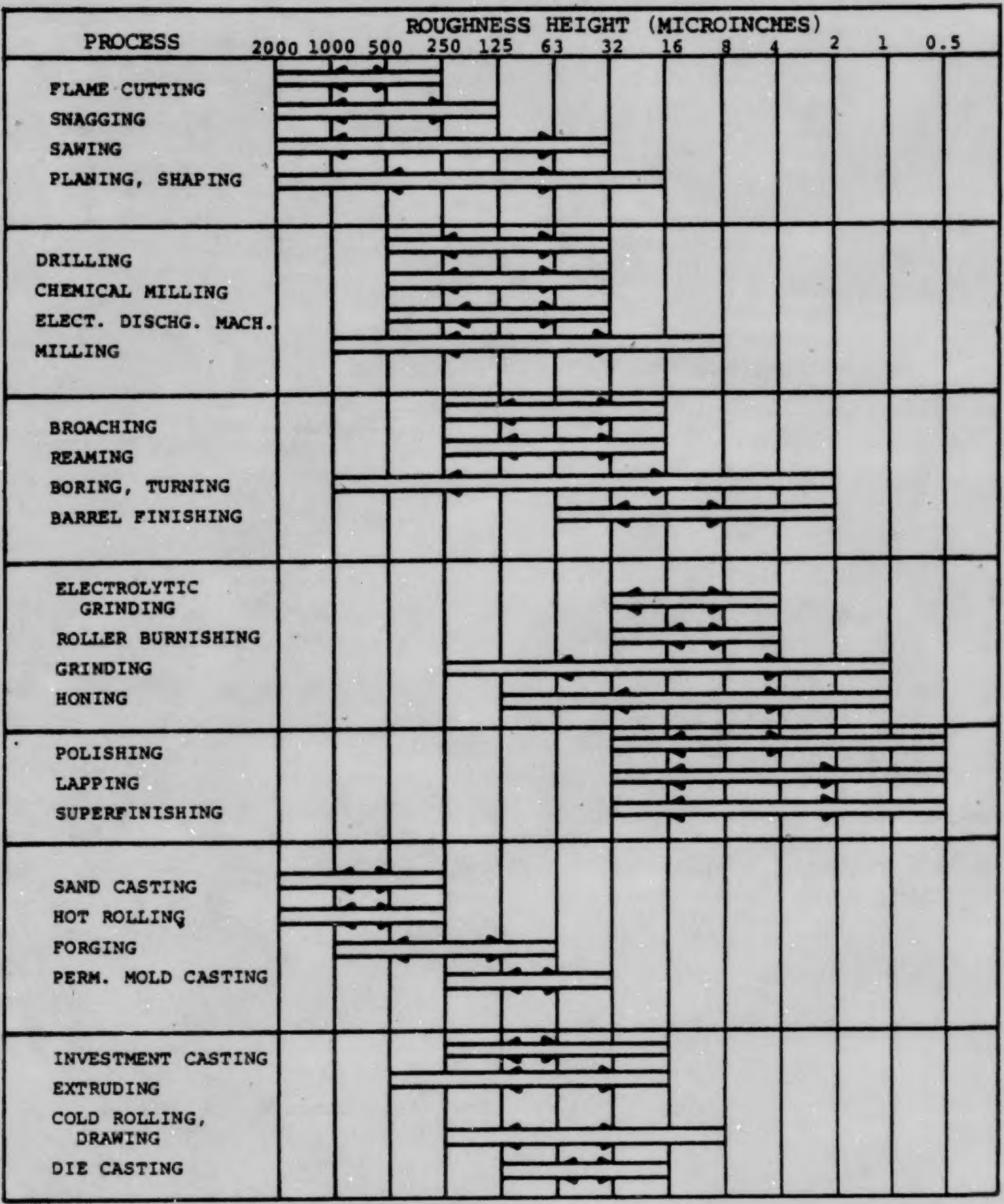
LAY SYMBOL	DESIGNATION	SKETCH OF SURFACE APPEARANCE	APPLICATION
∥	Lay parallel to the line representing the surface to which the symbol is applied.		
⊥	Lay perpendicular to the line representing the surface to which the symbol is applied.		
X	Lay angular in both directions to line representing the surface to which symbol is applied.		
M	Lay multidirectional.		
C	Lay approximately circular relative to the center of the surface to which the symbol is applied.		
R	Lay approximately radial relative to the center of the surface to which the symbol is applied.		

Table 27-4-3 Surface Texture Production



⟺ AVERAGE APPLICATION

▭ LESS FREQUENT APPLICATION

The ranges shown are typical of the processes listed. Higher or lower values may be obtained under special conditions.

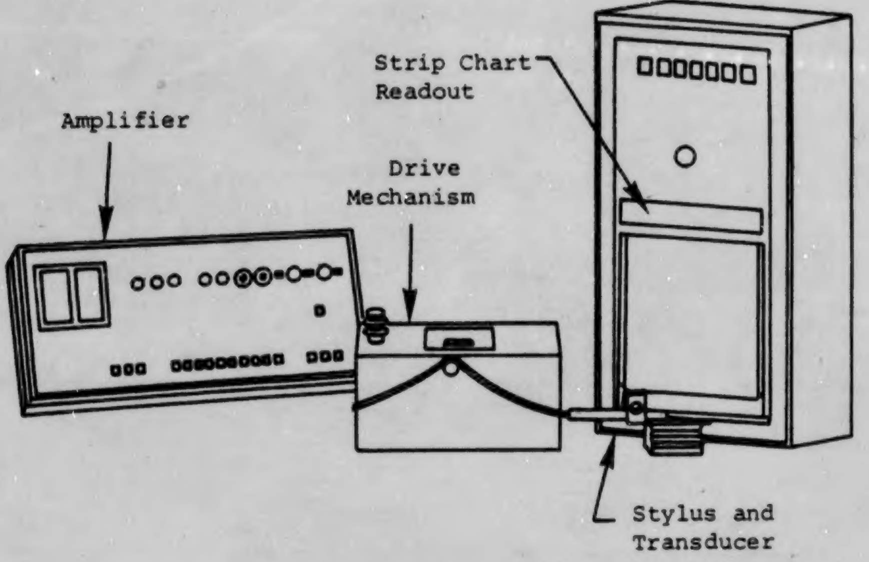


Figure 27-4-16 Surface Texture Stylus System

The stylus is basically a conically shaped needle with a diamond tip. The tip has a spherical vertex with a radius commonly of 0.0001 in. or 0.0005 in. The small radius permits the stylus to follow very small variations in surface texture.

The transducer converts the movement of the stylus into proportional electrical signals. Piezoelectric, electromagnetic and linear variable differential transformer systems are typically used as transducers.

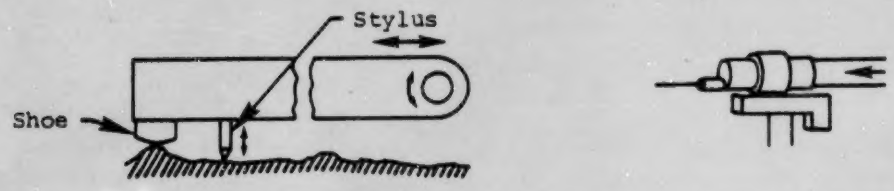
The drive mechanism traverses the stylus over the surface being measured. For accurate results, a uniform speed is essential. Most instruments feature various traversing speeds and stroke length which can be selected. Also, reciprocating traversal is frequently provided. The purpose of a reciprocating traversal is to increase the time of measurement to permit convenient readout on a meter.

The amplifier contains circuitry not only for amplification of the transducer's output but also for analyzing the output. Such amplifier analysis provides for meter readout in terms of roughness height. For instruments equipped with recording charts, readout is a trace on a known scale which permits measurement of average roughness, actual roughness, waviness height and width, and total texture (roughness superimposed on waviness).

Principles of Use

In the measurement of surface texture, stylus movement in relation to a reference plane provides the basic variable for analysis. The factors affecting the basic variable or the analysis thereof must be known for a meaningful readout. Such factors include the selection of the reference plane, the settings of instrument variables and the inherent features of the instrument.

- Reference Plane - The surface to be measured or an extraneous plane parallel to that surface provides the reference plane. Figure 27-4-16 illustrates two ways to provide the reference surface. The measured surface can provide the reference surface and the basic measurement is the difference in movement between the shoe and stylus. The shoe is selected to have a radius of at least eight times the roughness-width cutoff to prevent entry of the shoe into most



Measured Surface Provides Reference Plane

External Surface Provides Reference Plane

Figure 27-4 -17 Reference Planes

irregularities. Straight line skids are also used. Thus, the reference plane is the profile of the surface being measured and the stylus senses variations from the profile. As described later, this type of reference plane is suitable for measuring roughness height but imposes limitations on measuring waviness. An external surface can be used to provide the reference plane. The stylus senses variations from the extraneous reference plane. This type of reference plane is suitable for measuring roughness height and waviness as well as charting actual roughness and profile.

- Direction of Traversal - The direction of traversal is always at right angles to the direction of lay. In this manner, the maximum roughness present is measured.
- Roughness-Width Cutoff - The roughness-width cutoff establishes the distance from which successive stylus data are averaged. It is always wider than the roughness width. If the drawing does not stipulate a value for roughness-width cutoff, it can be determined from Tables in ASA B46.1 if the roughness-width is known. For machining processes, the machine traversal speed equals the roughness-width. For example, machine traversal of 0.015 inch per revolution equals 0.015 inch roughness width. If roughness cannot be determined, a cutoff of 0.030 inch is used.
- Length of Stroke - ASA B46.1 establishes a standard length for measuring roughness height as twenty times the roughness-width cutoff. This assumes that the specific surface examined

is representative of the entire surface. Accordingly, the inspector sets up the equipment to measure what appears to be the area having most roughness. Most instruments continuously average the values from the transducer even when a reciprocating stroke is employed. For such instruments the stroke need not be in one direction only. For example, for an 0.030 in. cutoff, the 0.6 in. stroke (20 x 0.030 in.) could be two cycles of a 0.150 in. reciprocating stroke.

- Roughness Averaging - The roughness averaging system typically consists of an AC amplifier, attenuators, averaging circuits, and a meter that reads roughness height in microinches. Output jacks permit hook-up to a chart recorder. Such an averaging system eliminates waviness from the data being averaged by the combination of traversal speed of the pickup head and the roughness-width cutoff. This is accomplished electronically by attenuating frequencies below a value expressed by Equation 27-4-4:

$$\text{Low Frequency Cutoff} = \frac{\text{Traversal Speed (in./sec)}}{\text{Roughness-Width Cutoff (in.)}} \quad \text{(Eq. 27-4-4)}$$

The relationship of the amplifier and drive unit settings must therefore, be known for each type of instrument used. Such relationship is described by literature provided by the equipment supplier (e.g., roughness-width cutoff settings are valid at 0.3 in./sec traversal speed.) The roughness-width cutoff identifies the maximum spacing of surface irregularities that are passed by the amplifier to the readout. For example, when an instrument's roughness-width cutoff setting of 0.030 is valid at a 0.3 in./sec traversal speed, it is known that irregularities spaced wider than 0.030 in. are blocked. Therefore, if a strip chart were connected to the amplifier's output, irregularities wider than 0.030 in. would not be recorded. Wider intervals can be recorded if traversal speed is slowed. For example, if the above traversal speed is slowed to 0.1 in./sec, the effective roughness-width cutoff is essentially three times the switch setting of 0.030 in. Shifting from an AC amplifier to a DC amplifier reduces the roughness width cutoff to zero and provides a theoretical infinite spacing that can be charted. However, if skids or shoes are used for the reference plane, a mechanical limit is imposed due to the skid following the wider irregularities. The mechanical limit is the radius of shoes divided by eight or for straight line skids, the length of stroke. The logical conclusion is that averaging systems are basically designed to measure roughness height and any other use requires careful analysis of the manufacturer's literature to determine the limitations associated with recording waviness or profile.

- Profiling - Profiling systems use a DC amplifier and a chart recorder that plots surface features on a calibrated scale. The system is basically designed to plot profile and essentially has a zero roughness-width cutoff or infinite spacing of irregularities that are recorded. However, use of skids or shoes for establishing the reference plane will introduce mechanical limits on the maximum spacing as previously described. The combination of recorder frequency response and traversal speed sets the limit on the narrowest spacing that will be recorded as expressed by the Equation 27-4-5:

$$\text{Narrowest Spacing (in.)} = \frac{\text{Traversal Speed (in./sec)}}{\text{Recorder Frequency Response (Hertz)}} \quad \text{(Eq. 27-4-5)}$$

For example, a traversal speed of 0.1 in./sec and a 100 Hertz frequency response gives the limit of 0.001 in. as the narrowest spacing that can be recorded. A much narrower spacing can be recorded if the traversal speed can be slowed considerably. Otherwise, difficulty exists in recording roughness of surfaces that are finished with finely spaced irregularities. Again, instrument capabilities must be known to determine the limitations of using profiling systems to plot roughness height.

Accuracy and Error Sources

Accuracy of roughness height and waviness measurements is primarily dependent on the equipment capabilities. Therefore, calibration methods are used to determine accuracy. For calibration of roughness height measurements, standard blocks having areas of precisely known roughness are traced and compared with indicated values. For example, the instrument may be adjusted to exactly match the 125 microinch roughness height area of a calibration block. Then other roughness areas of the standard are traced and the readout is plotted to establish a calibration curve. The deviation between the readout and the known roughness of the standard provides the error by which measurement of product are corrected.

For calibration of waviness measurements, standard blocks having known small step changes in contour are traced. The readout is compared with the known values to determine error. Gage blocks can also be arranged to provide a stepped calibration block.

Applications

Surface texture measurements are specified by engineering drawings when the surface roughness plays an important role in the function of that surface.

- Resistance to Wear - Roughness of load bearing surfaces tends to expose peaks to the load and results in increased wear. Also, deformation can result due to localization of stresses at points of excess roughness. This becomes very important on the leading flank of gears.
- Supportive of Lubricating Film - Excessive roughness provides peaks above the level of lubricating film causing metal-to-metal contact which should have been eliminated by the film. Conversely, some roughness is necessary to drag the lubricant between moving members.
- Clearance of Mating Parts - Roughness of the part or the sensor of the measuring device causes the dimensional inspection results to portray a larger material condition than actually exists. Therefore, close fit conditions are not actually met. Such effect on gage block stacks would be staggering were it not for the fine surface texture required of gage blocks.

- Resistance to Corrosion - Roughness tends to trap corrosive materials and serve as cells of incipient corrosion.
- Low Coefficient of Friction - Roughness plays a crucial role in the friction of ball and roller bearings and sliding surfaces.
- Esthetic Value - Many products have low roughness for sake of appearance. Automobile bodies are an example. In nuclear power plants, another driving factor is the ability to decontaminate the surface should radioactive material come into contact with that surface. Therefore, working surfaces in a radiation laboratory frequently use sheet metals having low roughness height.

EXERCISES

The following exercises reinforce the information presented in this module.

1. Given assignments to students/trainees to make angular measurements with a universal bevel protractor. Any parts with angles which are accessible by the bevel protractor may be used. Each assignment should require the student/trainee to demonstrate proficiency in (1) manipulative skills, including comfortable handling of the device, accurate placement of straight edges against angle boundaries, and adjustment of thumb lock nut without affecting the measurement, and (2) readout skills, including ability to differentiate between direct angles and supplements, and accurate reading of vernier.
2. Give assignments to students/trainees to make angular measurements with sine bars. Parts selected for measurement should contain angular features which are toleranced to one degree or less. Table 27-4-4 is a data table for use with each assignment.
3. Give assignments to students/trainees to make linear and angular measurements with engineering microscopes. Prior to such assignments, instruction should be given on the operation of the particular engineering microscope available for use. Each assignment should develop the skills of (1) establishment of datum, including part mounting for either silhouetting or reflecting image and perpendicularity of feature plane with optical system, (2) indexing of part, with and without supplementary gage blocks, and (3) accurate readout, including scale interpretation and accurate calculations.
4. Give assignments to students/trainees to make linear, angular and/or thread form measurements with optical

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projectors. Prior to such assignments, instruction should be given on the operation of the particular optical projector to be used. Each assignment should require demonstration of (1) establishment of datum, including part mounting and parallelism of feature plane to optical system, (2) selection of chart-gage to match part feature to be measured, (3) manipulation, including staging of chart-gage, and (4) accurate readout.

5. Give assignments to students/trainees to measure surface texture in terms of roughness height and waviness. Prior to such assignments, instruction should be given on the specific surface texture measuring equipment to be used. Each assignment should require demonstration of (1) calculation of roughness-width cutoff, (2) establishment of reference plane, (3) set-up, including stroke length, traversal speed and equipment settings, and (4) readout, including meter for roughness height and chart for waviness.

MATERIALS

The following materials are required to support this module:

1. Universal Bevel Protractor
2. Sine Bar
3. Gage Block Set
4. Height Indicator Gage (Mechanical or Electronic)
5. Universal Measuring Microscope or Similar Instrument Employing an Engineering Microscope

6. Optical Projector
7. Gage-Charts for Optical Projector (Specific types of match part features to be measured)
8. Stylus Trace Type of Surface Texture Measuring Equipment (Averaging or Profiling Equipment or Both)
9. Parts for Measurement, Features should include Acute and Obtuse Angles, Screw Threads, Inside and Outside Dimensions, Geometric Forms of Parallelism and Perpendicularity)

PROCEDURES

The suggested exercises involve a series of measurements using the following equipment. The following procedure is intended to assist the instructor/student in performing these exercises. It is also suggested that the student/trainee make reference to the discussion given in this module for further details.

Universal Bevel Protractor

1. The universal bevel protractor provides for the direct measurement of angles or their supplements by placement of precision straight edges on the boundaries of the angle.
2. Readout begins at the vernier zero and concludes with the vernier line which is coincident to a primary scale line in the same direction as from zero of the primary scale.

3. In actual measurements, one must be observant of whether the readout is the measured angle or its supplement.
4. Perform an angular measurement of an acute, obtuse and a straight angle reading the angular measure to the nearest 5 minutes.
5. Instrument error sources include straightness of the blade edges, bearing accuracy of the rotatable blade, and scale accuracy.
6. Procedural error sources include manipulative errors, readout errors, and unclear bearing surfaces.

Sine Bar

1. The sine bar (or block or plate) provides a constant hypotenuse of known length which can be used with gage blocks and height indicators for the measurement of angles.
2. Given the value of the angle by the part drawing, the gage block height needed for the measurement can be calculated by the formula $h = c \text{ sine } \theta$.
3. In determining gage block height, attention must be given to the method of mounting the part on the sine bar because the method of mounting can affect the relationship of the sine bar plane to the part feature.
4. Measurement of height deviation permits calculation of angular deviation by the formula $\tan \phi = \frac{i}{\ell}$.
5. Using the sine bar and gage blocks, measure the angle of a metal block cut at an angle similar to the example shown on page 27-4-15 of this module. Measure the angle to the nearest 10 seconds of arc.
6. Repeat step 5 for a second block.

7. Error sources of the sine bar are flatness and squareness of working surface, roundness and straightness of cylinders, parallelism of cylinders with each other and the working surface, and accuracy of the center distance between cylinders.
8. Error sources of measurements with sine bars include misalignment in the mounting of parts, precision of measuring the length over which the height variation is explored, errors of the height gage, flatness of the surface plate, and calculation errors.
9. Sine bars are preferred over universal bevel protractors when angles are inaccessible to the bevel protractor or when angles are toleranced in minutes.

Engineering Microscope

1. Engineering microscopes are optically assisted instruments for measuring lengths, angles, and forms.
2. The optical system permits accurate silhouetting or reflecting a part feature against a graduated scale.
3. Measurements are taken from micrometer lead screws, graduated scales within the optics system, or the combination of these two.
4. Angular measurements are provided by a protractor within the graticle chamber.
5. Measure the length of a gage block to the nearest 0.001 inch.
6. Using the engineering microscope, measure the angle of an angular block as previously done with a sine bar, but read the answer to the nearest minute of arc.

Optical Projector

1. Optical projectors are optically assisted instruments which project the part image on a screen for the measurement of lengths, angles and forms.
2. A silhouetting or reflecting image may be projected dependent on the design of the specific optical projector.
3. Basic components of any optical projector include light source, collimating lens system, workpiece positioning table, mirrors and lenses, viewing screen, and chart gages.
4. The two basic uses of optical projectors is for linear measurements and comparative measurements.
5. The three basic measurement techniques are comparison, movement, and translation.
6. Angular measurements are made by use of protractor rings to which the chart gage is mounted.
7. Using the optical projector, measure the angle of an angular block. Measure the angle to the nearest 30 minutes.
8. Measure the dimensions of a not go gage using an optical projector.

Surface Texture Measurement

1. Surface texture refers to roughness, waviness and lay.
2. Roughness is the finer irregularities in surface texture and is measured in roughness height expressed as the arithmetical average deviation from the center line in microinches.
3. Roughness-width cutoff establishes the greatest spacing of irregularities to be included in the roughness height measurement.

4. Waviness is the widely spaced component of surface texture and is generally wider than the roughness width cutoff. Its height is expressed as the peak to valley distance in inches.
5. Lay is the direction of the predominant surface pattern and is specified on drawings by the following symbols:

SYMBOL	DESIGNATION
$\parallel$	Parallel
$\perp$	Perpendicular
X	Angular in Two Directions
M	Multidirections
C	Circular
R	Radial

6. Using a surface texture stylus system, similar to that described in Figure 27-4-15, make measurements of:
   a. Roughness height
   b. Roughness width
   c. Roughness width
   d. Roughness height

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DATA TABLE

Table 27-4-4 Sine Bar Data Table

Equipment Serial Number

Sine Bar ______________ Height Gage ______________

Surface Plate ______________ Test Indicator ______________

Part Description

Name ______________ Serial Number ______________

Feature (Sketch the feature and label with tolerance.)

Calculations

Gage Block Height ($h = c \sin \theta$):

Variation of angle being measured ($\tan \phi = \frac{i}{\ell}$)

Value of angle measured:

REFERENCE MATERIALS

ASA B46-1-1962, Surface Texture, The American Society of Mechanical Engineers, New York New York

Busch, Ted, Fundamentals of Dimensional Measurement, Delmar Publishers

Farago, Francis T., Handbook of Dimensional Measurement, Industrial Press, Inc.

Handbook of Industrial Metrology, Society of Manufacturing Engineers, Prentice-Hall, Inc.

TEST

Read each question carefully. Be sure to provide the specific information each question requires. Make your answer brief. Use the backs of the test if you need more space.

1. Describe how angles are measured with the universal bevel protractor.

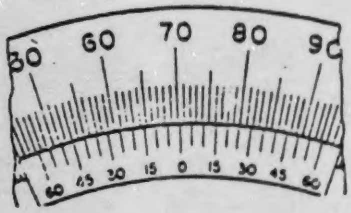
2. Name three sources of error in measurements with the universal bevel protractor.

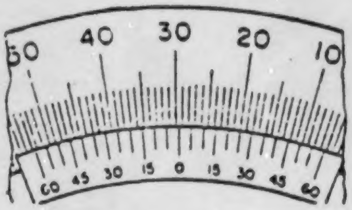
   a. ____________________

   b. ____________________

   c. ____________________

3. Give the reading the universal bevel protractor scales illustrated below:


50
60
70
80
90
60
45
30
15
0
15
30
45
60


50
40
30
20
10
60
45
30
15
0
15
30
45
60

Needs a. Reading ____________________ also

b. Reading ____________________.

4. Describe how angles are measured with a sine bar.

5. Name three error sources associated with measurements with the sine bar.

a.

b.

c.

6. Describe how angles are measured with the engineering microscope.

7. Name three error sources associated with measurements with the engineering microscope.

a. ______________________________

____

b. ______________________________

____

c. ______________________________

____

8. Describe how angles are measured with the optical projector.

____

____

____

____

____

____

____

____

9. Name three error sources associated with measurements with optical projectors.

a. ______________________________

____

b. ______________________________

____

c. ______________________________

____

10. Describe how an optical projector is used to measure form such as thread form.

____

____

11. Define the following terms related to surface texture:

a. Roughness ____

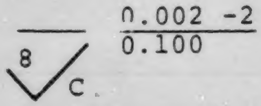
b. Roughness height ____

c. Roughness-width cutoff ____

d. Waviness ____

e. Lay ____

12. What is the meaning of the following symbol?



a. Basic symbol is:
b. 8 means:
c. 0.002 means:
d. 2 means:
e. 0.100 means:
f. C means:

13. Describe how the inspector determines the direction of traversal of the stylus used for surface texture measurement. Why is this direction used?

14. Describe why roughness height measuring equipment which uses the profile of the measured surface as the reference plane imposes limitation on measuring waviness with the same equipment.

15. Describe the use of standard roughness blocks with respect to roughness measuring equipment.

NUCLEAR TECHNOLOGY

MODULE 27 - 5

TOLERANCING

COURSE 27: METROLOGY

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 27 METROLOGY

MODULE 27-1	Fundamentals of Metrology
MODULE 27-2	Fixed Gages, Dividers, Calipers and Micrometers
MODULE 27-3	Gage Blocks, Mechanical Comparators and Electronic Comparators
MODULE 27-4	Angle Measurement Instruments, Optical Projectors and Surface Texture Gages
MODULE 27-5	Tolerancing
MODULE 27-6	Calibration
MODULE 27-7	Statistical Techniques in Metrology
MODULE 27-8	The Total Measurement System

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INTRODUCTION

The sizes of individual features normally give insufficient information to produce a part as envisioned by the designer. In addition to size of a feature, the form of the feature can be of importance, e.g., straightness, flatness, roundness, and profile. Also, the form of the feature with respect to other features can be of importance, e.g., angularity, perpendicularity, parallelism, and runout. In addition, the location of the feature with respect to other features can be of importance, e.g., position, concentricity, and symmetry. The axiom "you can't fit a square peg in a round hole" basically summarizes the need for form and location control.

The American National Standard ANSI Y14.5-1973, Dimensioning and Tolerancing, is used throughout the nuclear industry as the standard method of applying form and location controls on drawings and interpreting the meaning of such controls. This module describes the application of ANSI Y14.5-1973 and gives guidance on interpreting form and location controls consistent with the national standard. In this regard, this module quotes three rules from ANSI Y14.5-1973 which serve as the basis of drawing interpretation with respect to form and location. The applicability of these rules is subsequently given as each characteristic of form and location is introduced.

The terminology introduced by this module is defined in Appendix A to the module.

The student/trainee should refer to the Appendix and to the three rules as necessary in studying the application of each characteristic of form and location.

MODULE PREREQUISITES

The student/trainee should be familiar with blueprint reading and should have completed courses in algebra and plane geometry. The student/trainee shall also have completed all previous modules of this course.

OBJECTIVES

Upon completion of this module, the student/trainee shall be able to do the following:

1. Define the basic terms of maximum material condition, least material condition, regardless of feature size, straightness, flatness, roundness, cylindricity, perpendicularity, parallelism, true position, concentricity, and runout.
2. Correctly interpret drawing requirements for size of individual features including bilateral, unilateral, and limit tolerancing.
3. Demonstrate application of rounding principles by correctly rounding given values.
4. Match geometric terms with their symbols.
5. Demonstrate the ability to interpret drawings by describing the applicable rule of tolerancing for a given geometric characteristic.
6. Demonstrate the ability to interpret drawings by measuring geometric characteristics of parts and comparing measured values with stated tolerances.

NOTES TO INSTRUCTOR / STUDENT

Laboratory exercises are recommended to develop student/trainee skills in making measurements of form and location. Measuring devices which will be necessary are those used for Modules 27-2, 27-3, and 27-4. Advance preparation will be necessary to provide for a selection of parts and instruments to be used for measurement of:

- Straightness
- Flatness
- Roundness
- Cylindricity
- Angularity
- Perpendicularity
- Parallelism
- Position
- Concentricity
- Symmetry
- Runout

SUBJECT MATTER

DEFINITIONS OF TERMS

Definitions of terms introduced by this module are given in Appendix A along with symbols representing such terms. The student/trainee should refer to Appendix A as each new term is introduced by the text. In addition, the definitions and symbols of the following terms should be memorized at the point of their introduction in the text:

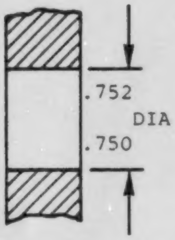
- Maximum Material Condition (MMC)
- Least Material Condition (LMC)
- Regardless of Feature Size (RFS)
- Straightness
- Flatness
- Roundness
- Cylindricity
- Perpendicularity
- Parallelism
- True Position
- Concentricity
- Runout

GENERAL TOLERANCING

Review of Engineering Drawing Applications

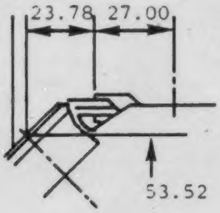
The dimensional inspector and QA/QC technician must correctly interpret engineering drawings in order to properly perform the inspection function. Tolerances may be expressed on drawings by any combination of the following:

- As specific limits or a tolerance applied directly to the dimension:



- In the form of a special note referring to specific dimensions:
  - NOTE: The 3.50 and 1.750 diameters apply after chrome plating.
- As specified in other documents referenced on the drawing for specific features:

See Detail
"M" Sheet 2



- In a general tolerance note referring to all dimensions on the drawing for which tolerances are not otherwise specified:

Tolerance Unless Otherwise Specified							
	Up To 6.00	Over 6.00 to 12.00	Over 12.00 to 24.00	Over 24.00 to 60.00	Over 60.00 to 120.00	Over 120.00 to 360.00	Over 360.00
All Dim.	± .12	± .18	± .26	± .38	+ .50 − .38	+ .76 − .50	+ 1.26 − .76
Angular Tolerance ± 1° Except Weld Geometry							
Weld Geometry +2° -0°							

In view of these four applications, persons responsible for the inspection function should develop a habitual practice of reviewing drawings prior to commencing an inspection activity. Such habitual review will tend to avoid misinterpretation or omission of drawing requirements. A recommended sequence for such review is:

- Review all drawing notes to determine those that apply to the inspection function.
- Review the general tolerancing note for familiarity with applicable tolerances where no other tolerancing methods are used.
- Review the specific dimensions to be inspected to determine the specific tolerancing method applicable to such dimensions.

Review of Tolerance Expression

Engineering drawings express dimensions and limits or tolerances with the same number of decimal places. For example:

Correct	Incorrect
0.870-0.875	0.87-0.875
0.500 ± 0.005	0.5 ± 0.005

The same expression is used in the inspection function when recording measured values. That is, the measured value is recorded to at least the same number of decimals as specified by the drawing.

Review of Dimensional Tolerancing Methods

Drawings specify the acceptable range of dimensions in one or two methods as follows:

- Limit Dimensional Method - The high limit (maximum value) is placed above the low limit (minimum value) or when expressed in a single line the low limit precedes the high limit and both are separated by a dash. Examples are:

  $\begin{matrix}0.750\\0.748\end{matrix}$ 0.748 - 0.750

- Plus and Minus Tolerancing Method - The dimension is given first and is followed by a plus and minus expression of tolerance. The plus and minus expression of tolerance may be unilaterial or bilateral.

Unilateral	Bilateral
$2.500 \pm \begin{matrix}0.000\\0.005\end{matrix}$	6.250 ± 0.005
$1..25 \pm \begin{matrix}0.003\\0.000\end{matrix}$	0.750 ± 0.001

Interpretation of Limits

All limits are absolute. Regardless of the number of decimal places, the limit is treated as if it were followed by an infinite number of zeroes. To determine conformance within limits, the measured value is compared directly with the limit and any deviation outside the limit signifies nonconformance.

The rule of any deviation signifying nonconformance is to be followed at all times by the inspection function. No matter how small the deviation outside the limit, the inspection function is not authorized to accept the deviation. Instead, an engineering review is necessary to determine the effect of the deviation on the fit, function, and interchangeability of the item.

There are special cases where the limits are waived because of engineering considerations. Such cases are documented to show that fit, function and interchangeability are not adversely affected. Such engineering decisions are not to be interpreted as negating the importance of the inspection activity nor indicating that a deviation is acceptable the next time it is detected. Each deviation must be evaluated on its own merits. If repetitive deviations are acceptable, engineering should change the limits such that the inspection function will not find measured values within the specified limits.

The above rule also brings to bear important concepts with respect to precision and as will be described later, the rounding of measured values. As described in Module 27-1, the element of precision that is termed discrimination becomes most important as limits are approached. In general the 10/1 or 4/1 rule described in Module 27-1 provides sufficient discrimination to permit directly comparing measured values with limits. But what happens when the measured value appears to be at the limit? The best rule to follow is to select a more discriminating inspection device that will measure to an additional decimal place. For example, a vernier micrometer reading of 2.5000 for a $2.5000\,^{+0.0000}_{-0.0005}$ dimension should result in a "referee" inspection with a device (e.g., test indicator) that has discrimination finer than 0.0001.

Rounding of Measured Values

Rounding of measured values is desirable to allow recording of inspection results to the same number of decimals places as the drawing requirement. When a number is to be rounded to fewer decimal places the following procedure applies:

- When the first digit discarded is less than 5, the last digit retained must not be changed. For example 3.46325 rounded to three decimal places is 3.463; the same value rounded to two decimal places 3.46.
- When the first digit discarded is greater than 5, or if it is a 5 followed by at least one digit other than 0, the last figure retained must be increased by one unit. For example: 8.37652 rounded to three decimal places is 8.377; the same value rounded to two decimal places is 8.38.
- When the first digit discarded is exactly 5, followed only by zeroes, the last digit retained must be rounded upward if it is an odd number, but not changed if it is an even number. For example: 4.365 rounded to two decimal places becomes 4.36; and 4.355 would also round to the same value, 4.36, if rounded to two decimal places.
- Measured values are rounded directly to the nearest value having the desired number of decimal places, rounding is not done in successive steps to less places. For example: 27.46 rounded to a whole number is 27. This is correct because the ".46" is less than one-half. 27.46 rounded to one decimal place is 27.5. But, if 27.5 is in turn rounded to a whole number, this is successive rounding and the result, 28, is incorrect.
- Rounding is accomplished after completion of calculations. In the following example of comparative measurements, premature rounding erroneously shows nonconformance:

Limit	Calculations		Premature Rounding
0.7505 Maximum	1.36435	(Feature)	1.3644
	-0.61385	(Datum)	-0.6138
	0.75050	(Result)	0.7506

- Rounding is not permitted to change a measured value from a nonconforming to a conforming state. For example, if 0.2251 is measured for a 0.225 maximum limit, the value of 0.2251 is reported and the item is considered as nonconforming.

FORM CONTROL

Affect of Size Features on Form

Engineering drawings illustrate size features as if they have perfect geometric form. However, the size limits or tolerances permit the feature to deviate from perfect geometric form. This is illustrated in Figure 27-5-1.

As indicated by Figure 27-5-1, limits of size without limits of geometric form permit variations in geometric form as long as the size limits are met. This means that the form of physical boundaries of the size feature can vary along the length of the boundaries provided much variation does not result in exceeding the size limits.

Unless otherwise specified, the size limits of an individual feature prescribe the extent within which variations of geometric form as well as size area allowed. This principle is illustrated by Figure 27-5-1 and it is expressed by Rule #1 as given by ASNI Y14.5-1973:

- Rule #1 - Unless otherwise specified, the limits of the dimension of an individual feature as well as its size. This control is defined as:

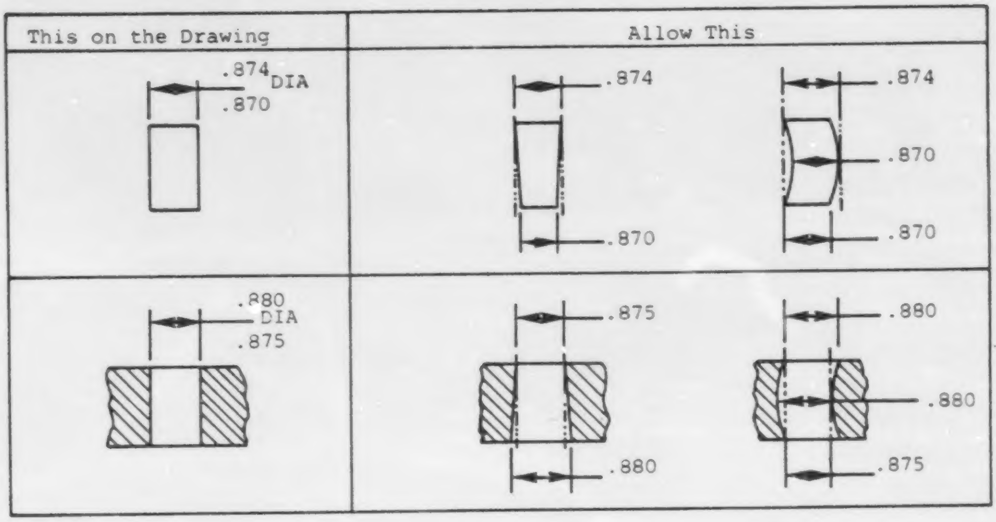

This on the Drawing
Allow This
.874
DIA
.870
.874
.870
.874
.870
.870
.880
DIA
.875
.875
.880
.880
.880
.880
.875

Figure 27-5-1 Extreme Variations of Form Allowed by a Size Tolerance

- No element of the actual feature shall be extend beyond a boundary of perfect form at Maximum Material Condition (MMC). (Except for material stock such as bars, sheets, and tubing where established standards specify such forms as straightness, flatness and others.) For the pin in Figure 27-5-1, this means that no portion of the pins outer surface can lie outside the boundary of a perfect cylinder whose diameter is 0.874.
- The actual size of the feature at any cross-section shall be within the Least Material Condition (LMC) limit. For the pin in Figure 27-5-1, this means that no measurement of pin diameter can be less than 0.870.

EXAMPLE: APPLICATION OF RULE #1

Given: The 0.875-0.880 diameter through hole illustrated in Figure 27-5-1.

Problem: If all diametrical points measure 0.875, what must be the form of the cylindrical boundaries of the hole?

Solution: Since the diameter at all points equals the limit at MMC, perfect cylindrical form must exist to avoid the extension of at least one element of the feature beyond a boundary of perfect form at MMC.

Problem: If the diameter measures 0.881 at one set of diametrical points but measures between 0.875 and 0.880 at all other diameters, is the feature acceptable?

Solution: No, because one cross-section of the feature lines outside the limit at LMC.

Effects of RFS

Where a position or form tolerance is specified on an RFS basis, the specified tolerance is independent of the size of the considered feature. The position or form tolerance is limited to the specified value regardless of the actual size of the feature. Likewise, referencing a datum feature on an RFS basis means that a centering about its axis or center plane is necessary, irrespective of the actual size of the feature.

Effect of MMC

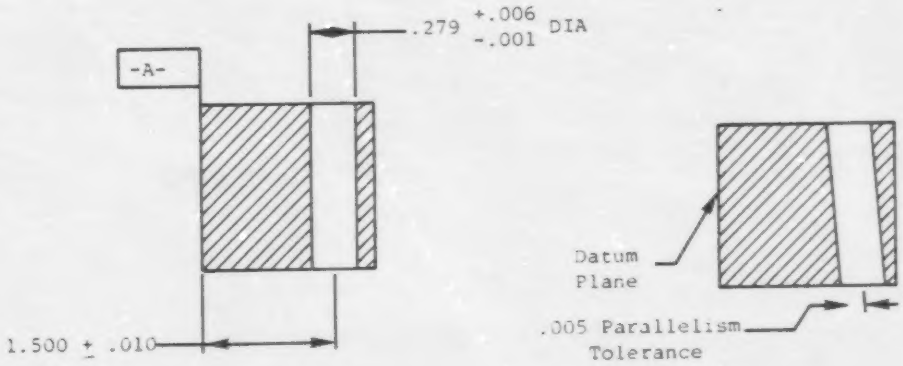
Where a tolerance of position or form is applied on an MCC basis, the specified tolerance is interdependent on the size of the considered feature. The tolerance is limited to the specified value if the feature is produced at its MCC limit of size. Where the actual size of the feature departed from MCC (in an acceptable direction), an increase in the tolerance is allowed equal to the amount of such departure. The total permissible variation in position or form is maximum when the features is at LMC. Likewise, referencing a datum feature on an MCC basis means the datum is the axis or center plane of a diameter or width fixed at the MMC limit of size of the feature. Where the actual size of the datum feature has departed from MMC, a deviation is allowed between its axis or centerplane and the datum axis or center plane.

Effect of Zero Tolerance at MCC

Where a tolerance of position or form is applied on a zero tolerance at MMC basis, the tolerance is totally dependent on the size of the considered feature. No tolerance is allowed if the feature is at its MMC limit of size; and in such case, it must be located at true position or be perfect in form, as applicable. Where the actual size of the feature has departed from MMC, a tolerance is allowed equal to the amount of such departure. The total permissible variation in position or form is maximum when the feature is at LMC, unless a maximum is specified.

EXAMPLE: RFS AND MCC TOLERANCING

Given: The part illustrated by the following drawing:



Problem: If the drawing specified 0.005 parallelism of the 0.279 diameter to datum A on an RFS basis, what effect would the actual size of the diameter have on the parallelism tolerance?

Solution: None. The tolerance applies regardless of feature size by definition. Irrespective of the actual size of the 0.279 diameter, the parallelism to datum A must be within a 0.005 tolerance zone which is illustrated as follows in an exaggerated manner:

Actual Feature Size	Parallelism Tolerance Allowed
0.278	0.005
0.280	0.007
0.282	0.009
0.285	0.012

Problem: If the drawing specified 0.005 parallelism of the 0.279 diameter to datum A on an MCC basis, what effect would the actual size of the diameter have on the parallelism tolerance?

Solution: The diameter's departure from 0.278 (which is MCC) is added to the 0.005 tolerance with the maximum addition equal to 0.007 at LMC. Such effect is illustrated by the following table:

ACTUAL FEATURE SIZE	PARALLELISM TOLERANCE ALLOWED
0.278	0.005
0.280	0.007
0.282	0.009
0.285	0.012

Problem: If the drawing specified the parallelism of the 0.279 diameter to datum A on a zero at MMC basis, what effect would the actual size of the diameter have on the parallelism tolerance?

Solution: At MMC (0.278 diameter), zero tolerance applies and the diameter must be perfectly parallel to datum A. As the actual size of the diameter approaches LMC, the deviation of the actual size from MMC equals the parallelism tolerance. The maximum tolerance is 0.007 which occurs when the diameter is at LMC (0.285).

Discussion: If one imagines a shaft inserted in the 0.279 diameter, the tightest fit will occur at MMC. Suppose that the engineer knows that the shaft center line will be fixed in a parallel position to datum A at assembly. If so, the parallelism tolerance is based on permitting assembly with both the shaft and the diameter at MMC. Dependent on the function of the assembly, the engineer selects either RFS or MMC tolerancing of the parallelism. If tightness of the fit is not particularly important, MMC would be selected because in effect it gives a bonus tolerance for manufacturing and therefore, less parts are likely to be rejected.

SYMBOLOGY

Symbols for Geometric Characteristics

The standard symbols for geometric characteristics as given by ANSI Y14.5-1973 are illustrated in Figure 27-5-2. These symbols are typically used on engineering drawings in lieu of spelling out the characteristics.

		Characteristic		Notes
Individual Features	Form Tolerances	Straightness	—	1
		Flatness	▱	1
		Roundness (Circularity)	○	
		Cylindricity	⌭	
Individual or Related Features		Profile of a Line	⌒	2
		Profile of a Surface	⌓	2
Related Features		Angularity	∠	
		Penpendicularity (Squareness)	⊥	
		Parallelism	//	3
	Location Tolerances	Position	⌖	
		Concentricity	◎	3, 7
		Symmetry	⌯	5
	Runout Tolerances	Circular	↗	4
		Total	↗	4, 6

Note: 1) The symbol ∼ formerly denoted flatness.
The symbol ⌒ or — formerly denoted flatness and straightness.

2) Considered "related" features where datums are specified.

3) The symbol || and ◉ formerly denoted parallelism and concentricity, respectively.

4) The symbol ↗ without the qualifier "CIRCULAR" formerly denoted total runout.

5) Where symmetry applies, it is preferred that the position symbol be used.

6) "TOTAL" must be specified under the feature control symbol.

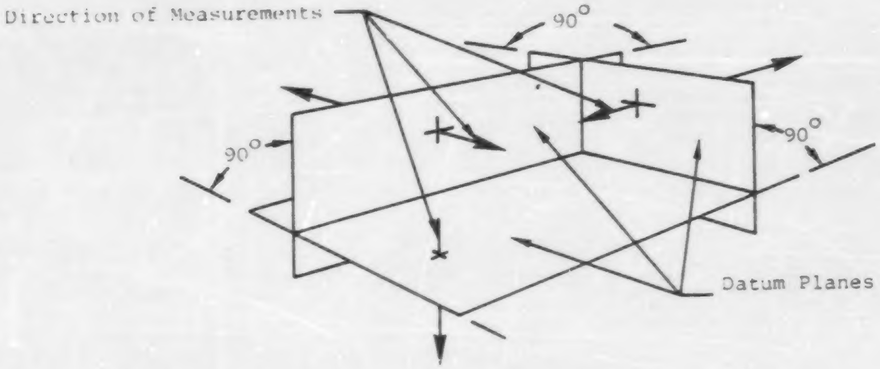
7) Consider the use of position or runout.

Where existing drawings using the above former symbols are continued in use, each former symbol denotes that geometric characteristic which is applicable to the specific type of feature shown.

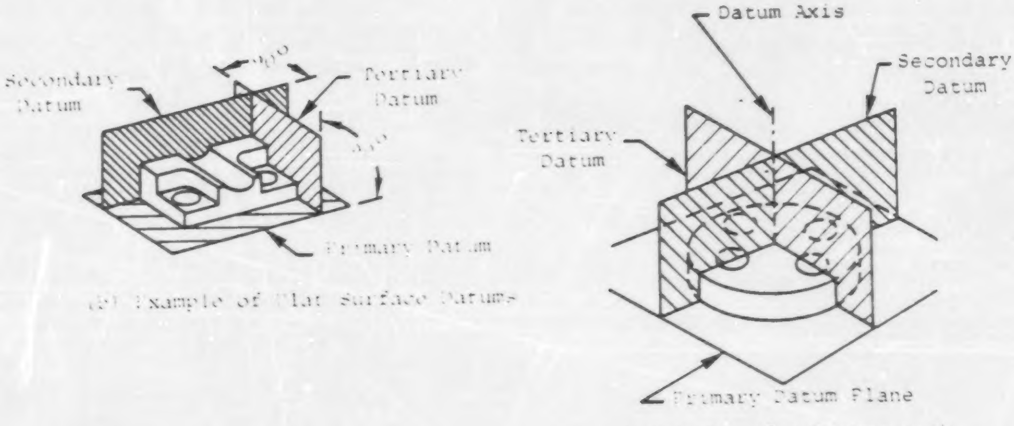
Figure 27-5-2 Geometric Characteristic Symbols

Datums and Their Symbols

Engineering drawings specify surfaces or other features which are most important to the design, as origins (datums) for dimensions. Sufficient features are indicated to position the part in relation to a set of three mutually perpendicular planes as illustrated in Figure 27-5-3. All related measurements of the part originate from these planes.


Direction of Measurements
90°
90°
90°
Datum Planes

(a) Datum Reference Planes


Secondary Datum
90°
Tertiary Datum
90°
Primary Datum
Datum Axis
Secondary Datum
Tertiary Datum
Primary Datum Plane

(b) Example of Flat Surface Datums

(c) Example of a Datums with Cylindrical Features

Figure 27-5-3 Reference Planes

Datums are identified in drawings by a boxed alpha designator as shown in Figure 27-5-4. Depending on the complexity of the part, the number of datums may range from one to several tens of datums. Each datum is given its own unique letter and all letters of the alphabet except I, O, and Q may be used. Where the single alpha series is exhausted, the double alpha series is used, i.e., AA through AZ.

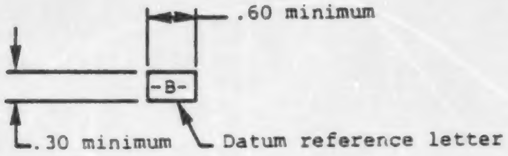


Figure 27-5-4 Datum Symbols and Size Thereof

Other Symbols

Other symbols commonly indicated on drawings are illustrated in Figure 27-5-5. Certain of these symbols are used with the feature control symbol which is described later.

Term	Abbreviation	Symbol
Maximum Material Condition	MMC	Ⓜ
Regardless of Future Size	RFS	Ⓢ
Diameter	DIA	ø
Projected Tolerance Zone	Tol Zone Proj	Ⓟ
Reference	REF	(1.250)
Basic	BSC	$\boxed{3.875}$

Figure 27-5-5 Other Symbols

Feature Control Symbols

The feature control symbol indicates a position or form tolerance. It consists of a frame containing the geometric characteristic symbol (See Figure 27-5-2), datum references (if any), RFS or MMC modifier as appropriate, (See Rules #2 and #3), the diameter symbol where applicable, and the tolerance of the geometric characteristic. The feature control symbol illustrated in Figure 27-5-6 is read as follows: the angularity of the feature shall be within 0.005 on an MMC basis to datum C regardless of datum C size and also to datums B and A on an MMC datum B and A basis.

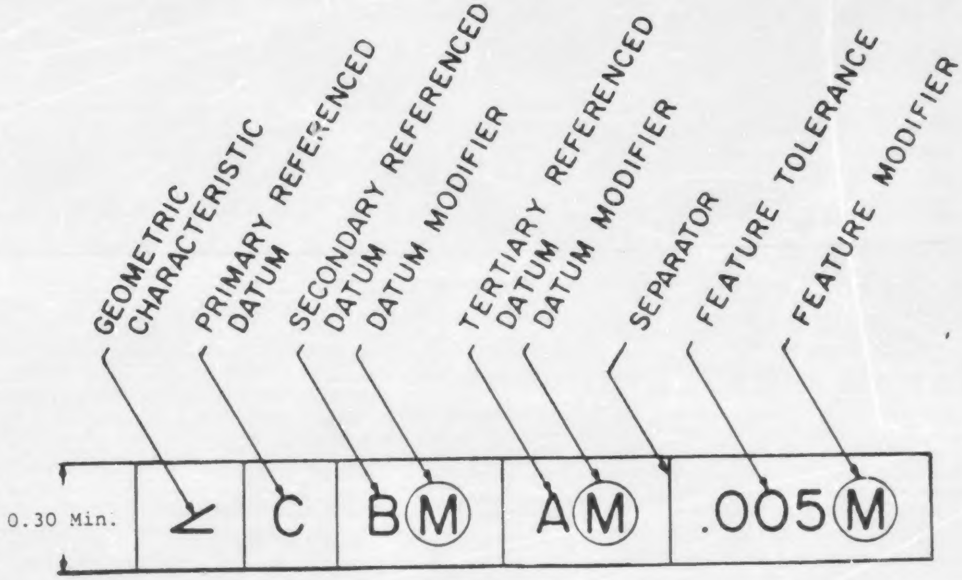

GEOMETRIC CHARACTERISTIC
PRIMARY REFERENCED DATUM
SECONDARY REFERENCED DATUM
DATUM MODIFIER
TERTIARY REFERENCED DATUM
DATUM MODIFIER
SEPARATOR
FEATURE TOLERANCE
FEATURE MODIFIER
0.30 Min.
∠
C
B Ⓜ
A Ⓜ
.005 Ⓜ

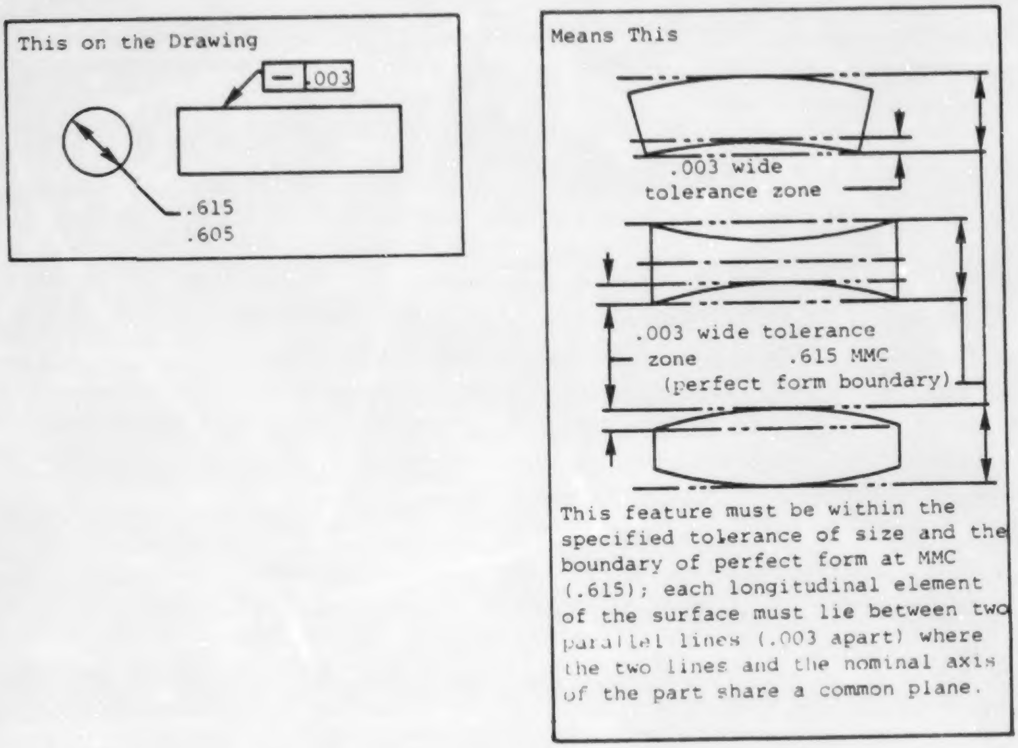
Figure 27-5-6 Illustration of Feature Control Symbol

FORM TOLERANCES

Form tolerances control straightness, flatness, roundness, cylindricity, profile, angularity, parallelism and perpendicularity (See Figure 27-5-2). Form tolerances are specified by the engineer where the size tolerances do not give the required control. Where the form tolerance value represents the diameter of a cylindrical zone, it is preceded in the feature control symbol by the diameter symbol.

Straightness

A straightness tolerance specifies a tolerance zone within which an axis or all points of the considered element must lie. It is applied in the drawing view where the elements to be controlled are represented by a straight line. Where straightness is specified independent of the individual size feature, Rule #1 also applies because one plane surface is the feature to be controlled. In such cases, a straightness tolerance smaller than the size tolerance serves to limit the variation in form. Figure 27-5-7 illustrates such a case. Per Rule #1, the size tolerance permits straightness of the pin in Figure 27-5-7 to vary from perfect straightness at MMC (0.615) to within 0.010 at LMC (0.605). However, the application of the straightness control feature in Figure 27-5-7 limits the maximum unstraightness of 0.003.

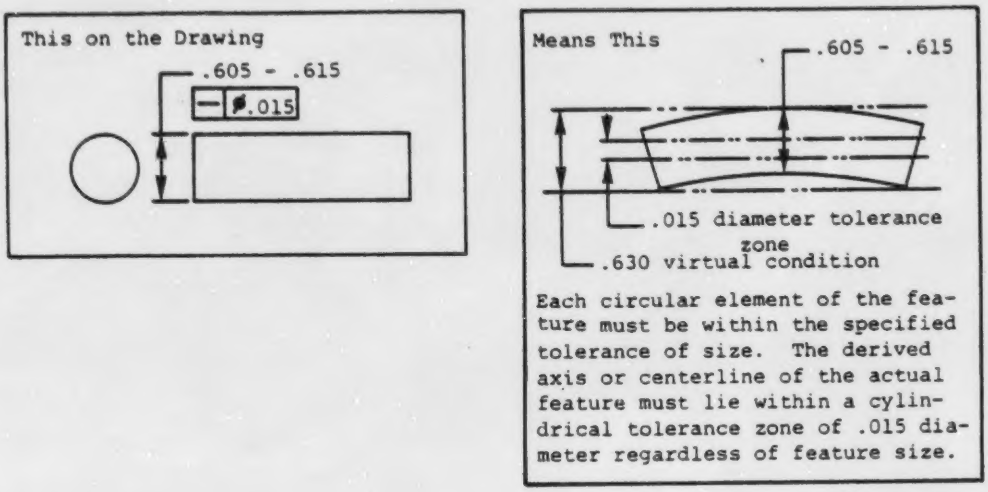

This on the Drawing
— .003
.615
.605
Means This
.003 wide
tolerance zone
.003 wide tolerance
zone
.615 MMC
(perfect form boundary)

This feature must be within the specified tolerance of size and the boundary of perfect form at MMC (.615); each longitudinal element of the surface must lie between two parallel lines (.003 apart) where the two lines and the nominal axis of the part share a common plane.

Figure 27-5-7 Straightness Tolerance Independent of Size Tolerance

Where straightness is specified with the size dimension such that the feature axis is being controlled, Rule #1 no longer applies. Instead, the straightness tolerance is applied on an RFS or MMC basis in accordance with Rule #3.

Figure 27-5-8 illustrates straightness specified with the size dimension on an RFS basis. The pin in this figure must be straight within the straightness tolerance of 0.015 regardless of the actual size of the pin's diameter. Since the straightness tolerance in this case depicts a diametrical zone, the diameter symbol precedes the straightness tolerance.



Each circular element of the feature must be within the specified tolerance of size. The derived axis or centerline of the actual feature must lie within a cylindrical tolerance zone of .015 diameter regardless of feature size.

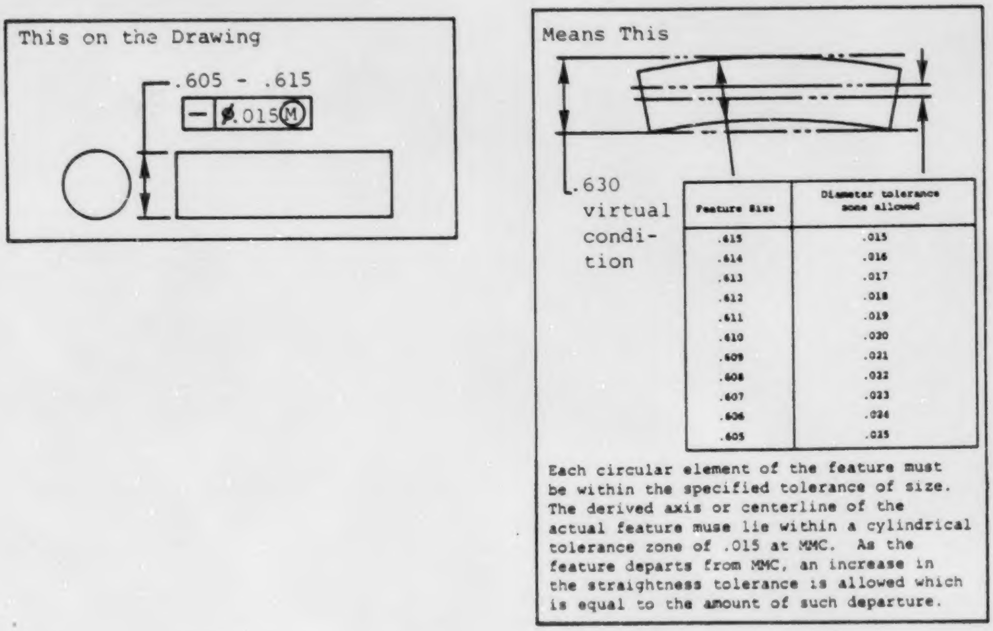
Figure 27-5-8 Straightness Tolerance With Size Feature on RFS Basis

Figure 27-5-9 illustrates straightness specified with the size dimension on an MMC basis. The pin in this figure must meet the straightness tolerance when the pin's diameter is at MMC. However, the deviation from MMC toward LMC of the diameter is added to the straightness tolerance.

Measurement of straightness employs the comparison of the feature element with a line or plane of known straightness. Several typical techniques are illustrated in Table 27-5-1. (Please refer to the next page for Table 27-5-1.)

Flatness

A flatness tolerance specifies a tolerance zone defined by two parallel planes within which the surface must lie. The flatness form control symbol is attached to a leader directed to the surface or extension line thereof in the drawing view where the surface is represented by a line. Since flatness is associated with a one plant surface, RFS



Feature Size	Diameter tolerance zone allowed
.615	.015
.614	.016
.613	.017
.612	.018
.611	.019
.610	.020
.609	.021
.608	.022
.607	.023
.606	.024
.605	.025

Each circular element of the feature must be within the specified tolerance of size. The derived axis or centerline of the actual feature muse lie within a cylindrical tolerance zone of .015 at MMC. As the feature departs from MMC, an increase in the straightness tolerance is allowed which is equal to the amount of such departure.

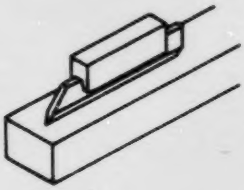
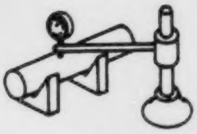
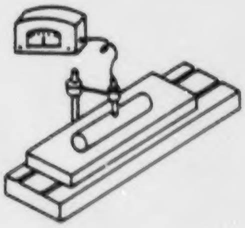
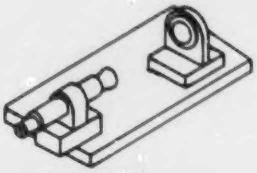
Figure 27-5-9 Straightness Tolerance With Size Feature on MMC Basis

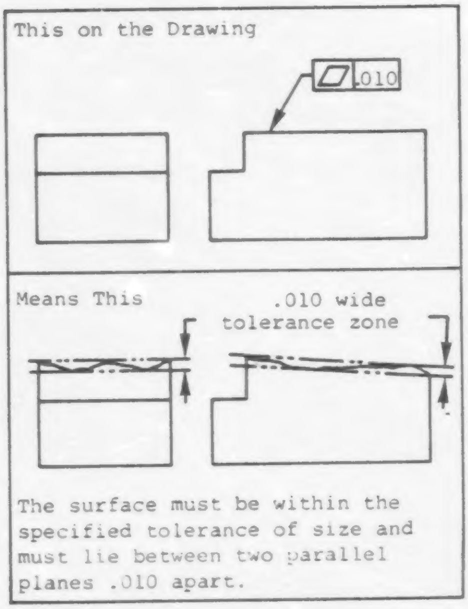
and MMC are not applicable. Rule #1 and the flatness tolerance control flatness as indicated in Figure 27-5-10.

Typical measurement techniques for inspecting flatness are illustrated in Table 27-5-2. The height gage is suitable for use where the indicator discrimination is 1/4 or finer of the flatness tolerance. The autocollimator system has the capability of measuring the flatness of surface plates and other relatively large surfaces having flatness tolerances in microinches. The optical flat has the ability to measure flatness to within a few microinches. It is used on small surfaces having stringent flatness requirem-ments such as the sensing surfaces of many measuring devices, (e.g., micrometer anvils).

Table 27-5-1

Straightness Inspections - Example Methods

Instruments	Diagram	Discussion
Knife edge rule		Toolmaker or reference quality knife edges having straightness accessories of about 0.00001 to 0.0001 are placed against the feature element. Ratio of contact of blueing or access by feeler gages provide inspection results.
Surface plate, vee blocks, height indicator gage		Part is staged on a surface plate which serves as the reference plane. Height indicator explores straightness of feature element. (NOTE: Similar inspection technique is use of bench centers to support the part from its axis.)
Precision slide and sensitive indicator		In this example, the height indicator is stationary and the part is moved with a precision slide. An electronic or mechanical test indicator measures variations in straightness. (A similar technique employs measuring machines whose indicator is mounted to precision slides.)
Optical telescope and optical targets		Optical targets moved along the feature element reflect variations in straightness as read by the optical telescope.



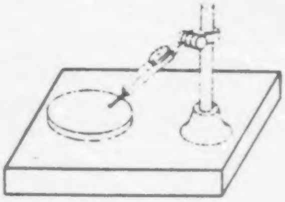
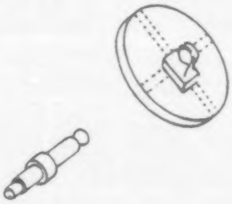
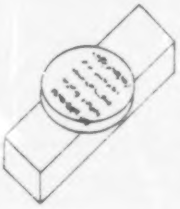
The surface must be within the specified tolerance of size and must lie between two parallel planes .010 apart.

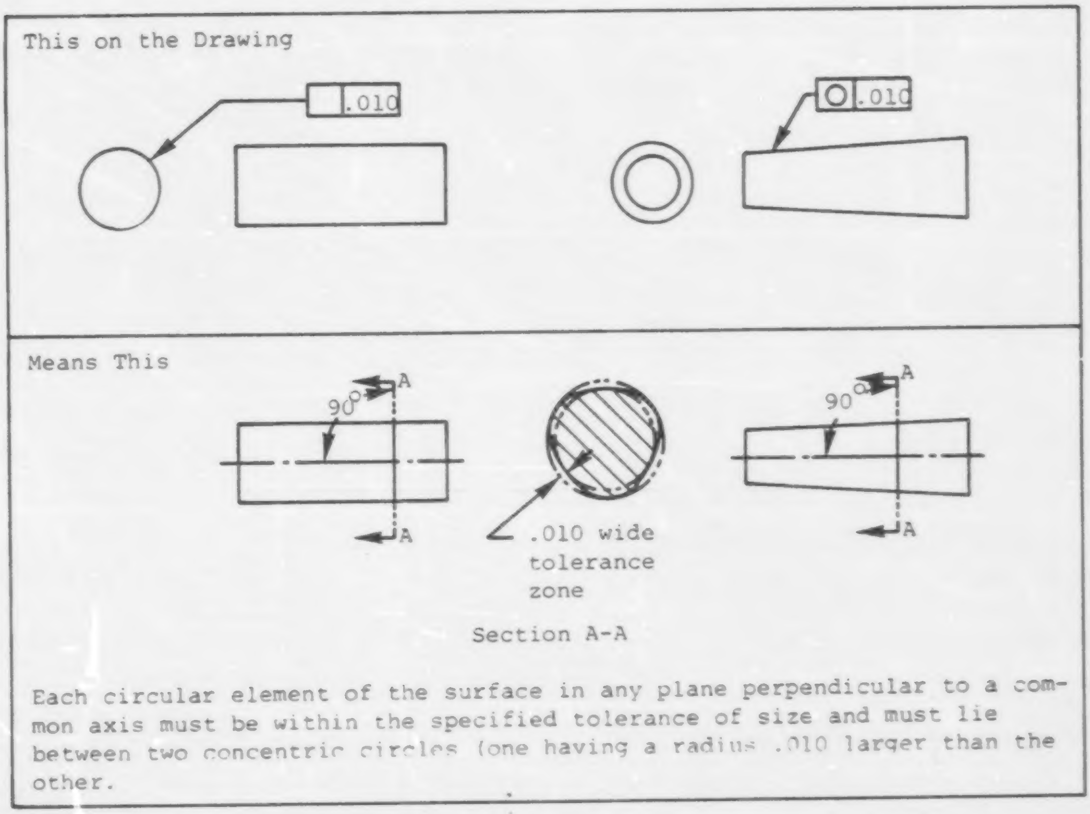
Figure 27-5-10 Flatness Form Control

Roundness

A roundness tolerance can apply to either a cylindrical, conical, or spherical feature. It establishes a diametrical tolerance zone within which a selected circular surface of the feature must lie. Thus, roundness is sometimes termed circularity. As illustrated in Figure 27-5-11, Rule #1 and the roundness tolerance apply when roundness is specified by the drawing. Rule #1 applies because the surface of the feature is being controlled by roundness.

Table 27-5-2
Flatness Inspection - Example Methods

Instrument	Diagram	Discussion
An indicator stand and a surface plate		The surface to be measured is first set up to be parallel to the surface plate. The indicator measures variations caused by unflatness.
Autocollimator and reflector with base having appropriate pad separation		As the reflector is moved along various lines of position, unflatness tilts the reflector. The autocollimator has an eye piece for direct reading of graticles or has a photoelectric sensor.
Optical flat with monochromatic light or plano-interferometer		Monochromatic light of known wavelength is reflected by the air wedge between the optical flat and the work piece such that dark bands are visible. At perfect flatness the bands are straight and spaced exactly one-half wavelength. The extent of curvature of the bands corresponds to the degree of unflatness.

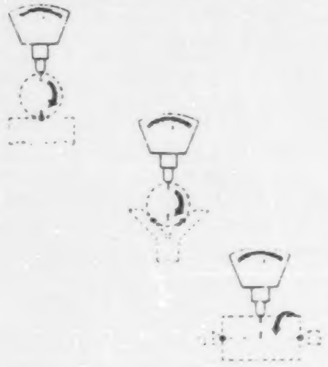
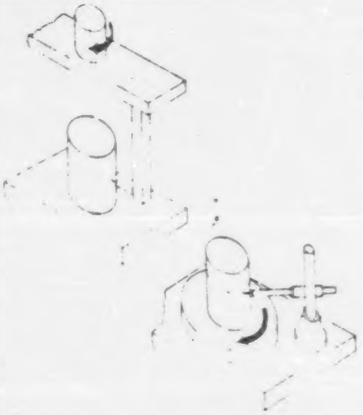


Each circular element of the surface in any plane perpendicular to a common axis must be within the specified tolerance of size and must lie between two concentric circles (one having a radius .010 larger than the other.

Figure 27-5-11 Roundness Form Control

Measurements of roundness are described in Table 27-5-3. The first type uses the feature as a reference datum. This type of roundness inspection compares diameters of the feature measured at a number of points. If permitted by the tolerance, standard inside and outside measuring devices, such as vernier calipers and micrometers, may also be used for this type of roundness inspection. Comparison of diameters for roundness inspection assumes that each diameter's center point falls on the same axis of the feature. It is also dependent on selecting both largest and smallest diameters within a radial plane. Therefore, comparison of diameters

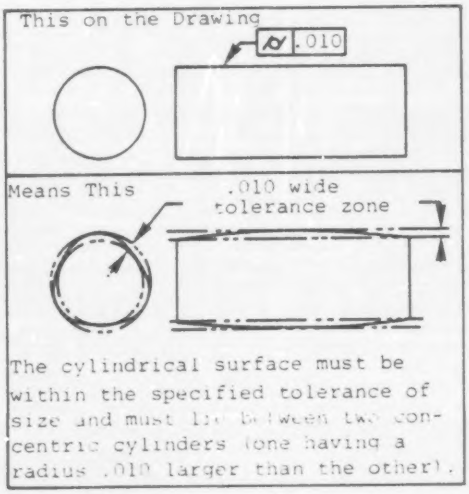
Table 27-5-3
Roundness Inspection - Example Methods

Instrument	Diagram	Discussion
Height Gage with: a. reference plane b. vee block c. bench-center		With the reference plane and vee block techniques, variations in feature diameter are representative of variations in roundness. The vee block tends to yield larger indicator readings than the actual out of roundness and normally requires use of correction factors. The bench-center technique measures variations in radial height from the axis of the feature.
Electronic Profiling System with: a. rotating spindle b. rotating table		Profile systems are commonly used to plot variations of the feature to a precision axis of rotation provided by the spindle or table. Such systems also permit determination of actual contour and count of the number of periodic departure from roundness such as lobes.

to determine roundness is suitable when roundness and not profile is the major concern. When the profile is of major concern, (i.e., the distribution pattern of departures from roundness is of concern), a profiling system is used for measuring roundness.

Cylindricity

A cylindricity tolerance establishes a tolerance zone bounded by two concentric cylinders within which the feature surface must lie. Therefore, unlike roundness, cylindricity applies simultaneously to the entire surface. As illustrated in Figure 27-5-12, Rule #1 and the cylindrical tolerance apply to the feature. Rule #1 applies because the surface of the feature is being controlled by cylindricity.



The cylindrical surface must be within the specified tolerance of size and must lie between two concentric cylinders (one having a radius .010 larger than the other).

Figure 27-5-12 Cylindricity Form Control

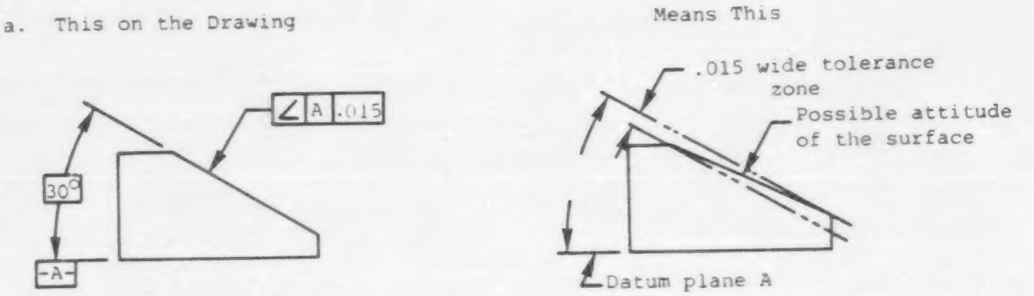
As described in Module 27-2, cylindricity can be measured on a GO-NOT GO basis by cylindrical plug and ring gages. In addition, the techniques of comparison of diameters listed in Table 27-5-3 measure cylindricity when applied along the axis of the feature.

Angularity

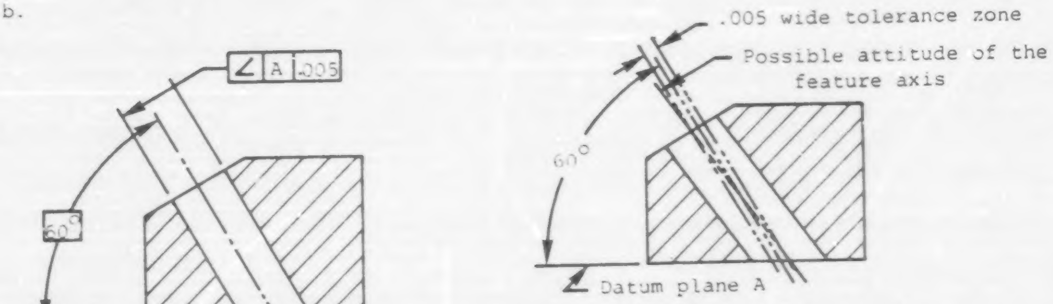
Angularity tolerancing establishes a tolerance zone defined by two parallel planes at the specified basic angle within which (a) the surface of the considered feature must lie or (b) the axis of the considered feature must lie. When an angularity tolerance is applied to a surface which forms an angular boundary, Rule #1 and the angularity tolerance apply. When an angularity tolerance is applied to the axis of a feature, RFS or MMC applies in accordance with Rule #3, Figure 27-5-13 illustrates these concepts.

Perpendicularity

Perpendicularity can be applied to a surface, axis, or diametrical axis. In the first two applications, the perpendicularity tolerance zone is defined by two parallel planes perpendicular to a datum plane or axis within which the considered surface or axis must lie. When applied with a diameter feature symbol, the perpendicularity tolerance zone is defined by a cylindrical tolerance zone perpendicular to a datum plane within which the axis of the considered feature must lie. Whenever either application pertains to the perpendicularity of an axis, Rule #3 applies. When applied to a surface, Rule #3 applies. When applied to a surface, Rule #1 applies. These concepts are illustrated in Figure 27-5-14, 27-5-15, and 27-5-16.


a. This on the Drawing
Means This
∠ A .015
30°
-A-
.015 wide tolerance zone
Possible attitude of the surface
Datum plane A

The surface must be within the specified tolerance of size and must lie between two parallel planes .015 apart which are inclined at 30° to the datum plane.

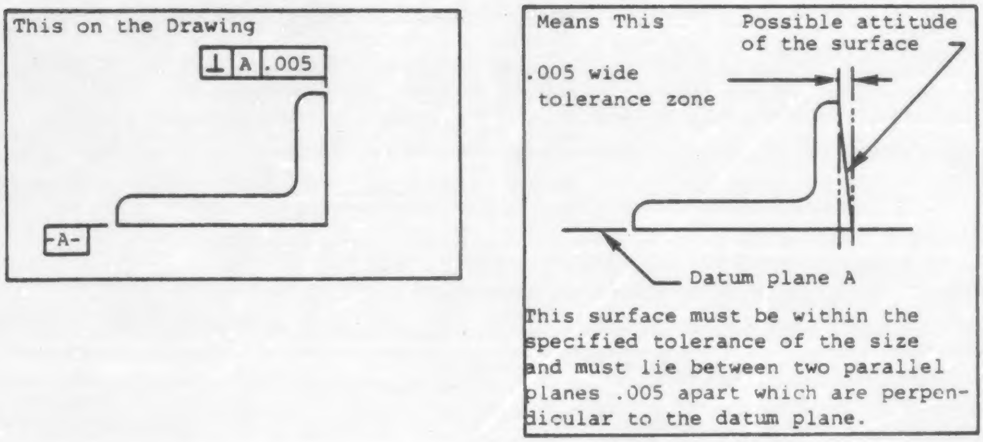

b.
∠ A .005
60°
-A-
.005 wide tolerance zone
Possible attitude of the feature axis
60°
Datum plane A

The feature axis must be within the specified tolerance of location and must lie between two parallel planes .005 apart which are included at 60° to the datum plane.

(RFS)

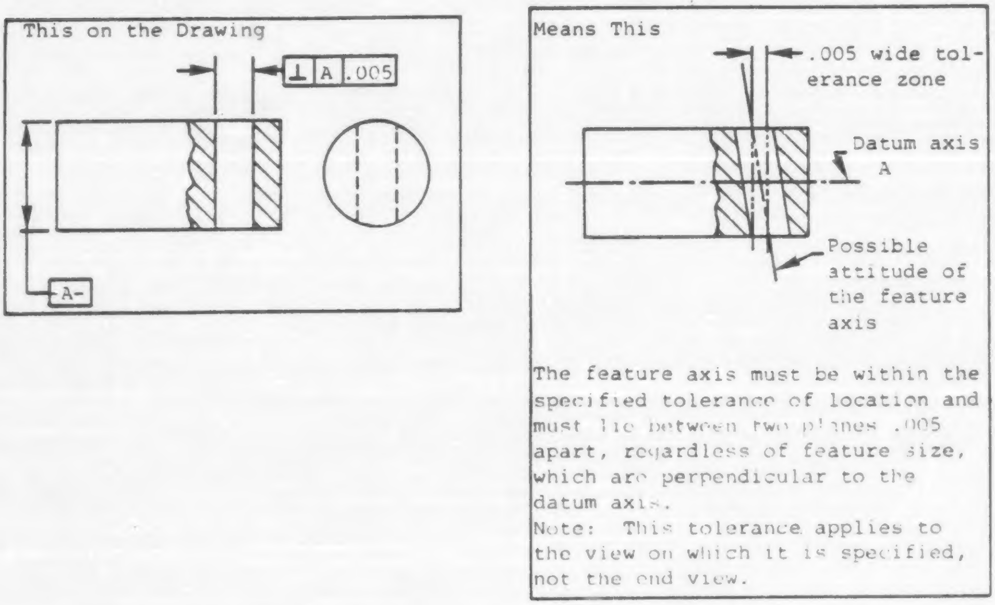
Figure 27-5-13 Angularity Form Control

Angularity is inspected by the methods described by Module 27-4.


This on the Drawing
⊥ A .005
-A-
Means This
Possible attitude of the surface
.005 wide tolerance zone
Datum plane A

This surface must be within the specified tolerance of the size and must lie between two parallel planes .005 apart which are perpendicular to the datum plane.

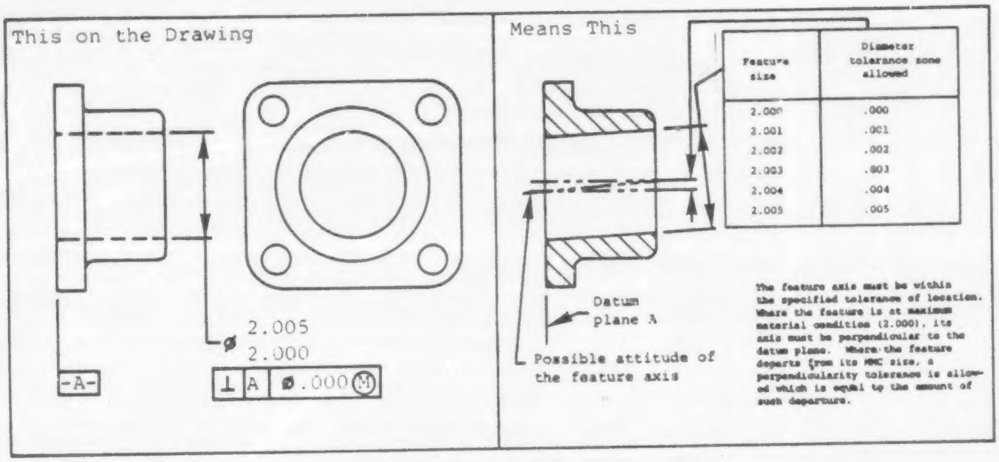
Figure 27-5-14 Perpendicularity Control of a Surface (Rule #1)


This on the Drawing
⊥ A .005
-A-
Means This
.005 wide tolerance zone
Datum axis A
Possible attitude of the feature axis

The feature axis must be within the specified tolerance of location and must lie between two planes .005 apart, regardless of feature size, which are perpendicular to the datum axis.

Note: This tolerance applies to the view on which it is specified, not the end view.

Figure 27-5-15 Perpendicularity Control of an Axis Without Diameter Symbol (Rule #3)



Feature size	Diameter tolerance zone allowed
2.000	.000
2.001	.001
2.002	.002
2.003	.003
2.004	.004
2.005	.005

The feature axis must be within the specified tolerance of location. Where the feature is at maximum material condition (2.000), its axis must be perpendicular to the datum plane. Where the feature departs from its MMC size, a perpendicularity tolerance is allowed which is equal to the amount of such departure.

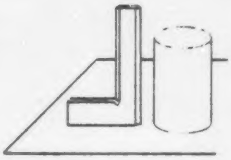
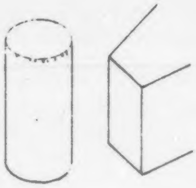
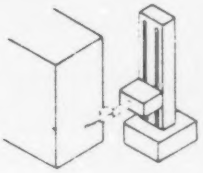
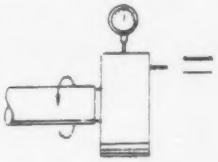
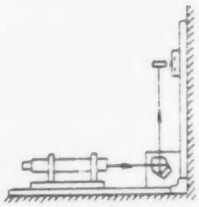
Figure 27-5-16 Perpendicularity Control With Diameter Symbol (Rule #3)

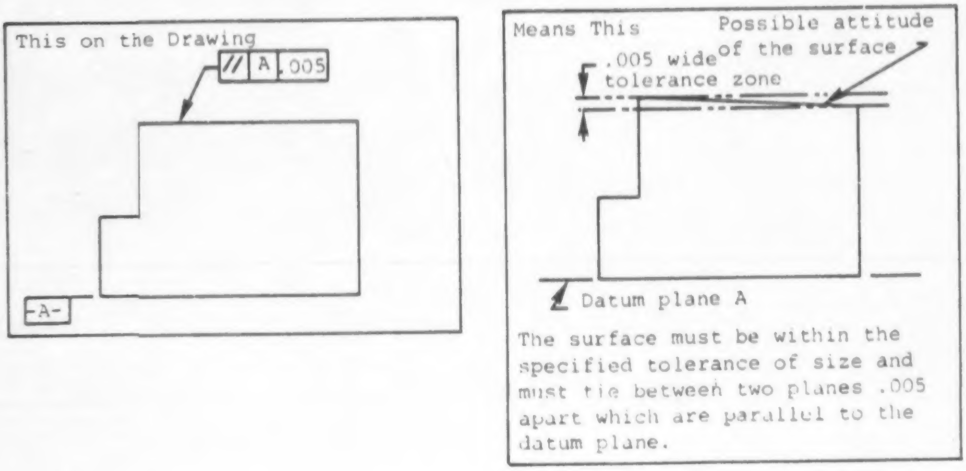
Example methods of measuring perpendicularity are given in Table 27-5-4 on the following page.

Parallelism

A tolerance of parallelism can be applied in the same manner as perpendicularity. When it applies to a surface or an axis with respect to a datum surface or axis, parallelism tolerance represents two planes or lines parallel to the datum within which the surface or axis of the considered feature must lie. When applied with the diameter feature symbol, parallelism tolerance represents a cylindrical tolerance zone parallel to the datum within which the axis of the considered feature must lie. When applied to a surface, Rule #1 also applies. When applied to an axis, RFS or MMC applies in accordance with Rule #3. These concepts are illustrated in Figures 27-5-17, 27-5-18, and 27-5-19.

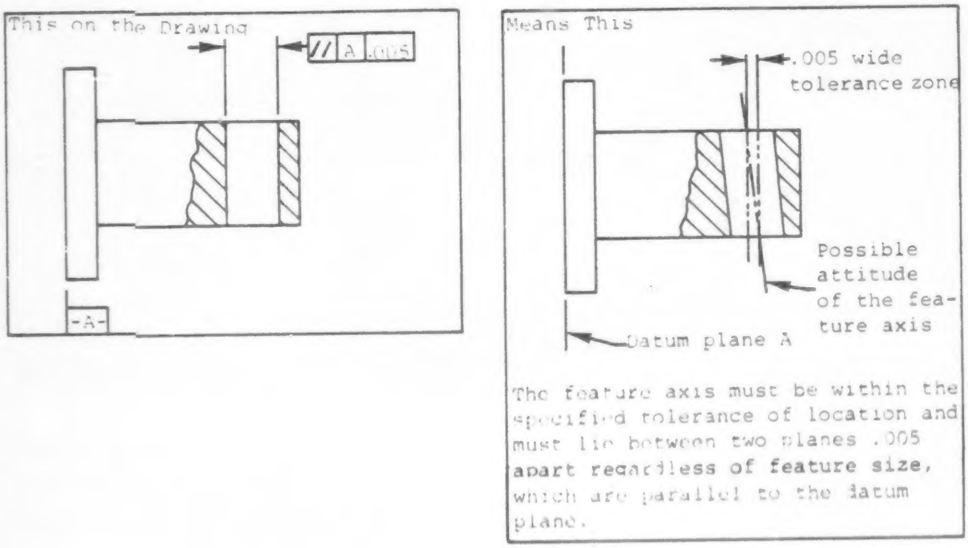
Table 27-5-4
Perpendicularity Measurement - Example Methods

Instruments	Sketch	Discussion
Toolmaker square		Both the part and the tool rest on a surface plate. Gap between the edge of the square and sections along the contacted object surface is either visually observed or measured with a feeler gage.
Cylindrical square, with one face off angle and with graduations on the surface		The cylindrical square is brought into contact with the surface to be measured for perpendicularity. Curved graduation lines on the cylinder surface indicate the tilt angle of the part surface, by rotating the cylinder to an orientation producing the least light gap.
Height gage stand with traveling indicator head		A special height gage stand with guideways to provide straight and vertical guidance to a head which carries an indicator in contact with the object surface.
Indicators and supporting members for the part		Variations from the perpendicular between two surfaces which are related to a common axis can be measured by rotating the part around that axis and indicating the runout of selected circular paths.
Autocollimator optical square and reflector		Aligning an autocollimator with the datum plane and turning the emitted light at a right angle with an optical square, permits measurement of perpendicularity by observing the reflection from a mirror moved along the inter-related plane.


This on the Drawing
// A .005
-A-
Means This
Possible attitude of the surface
.005 wide tolerance zone
Datum plane A

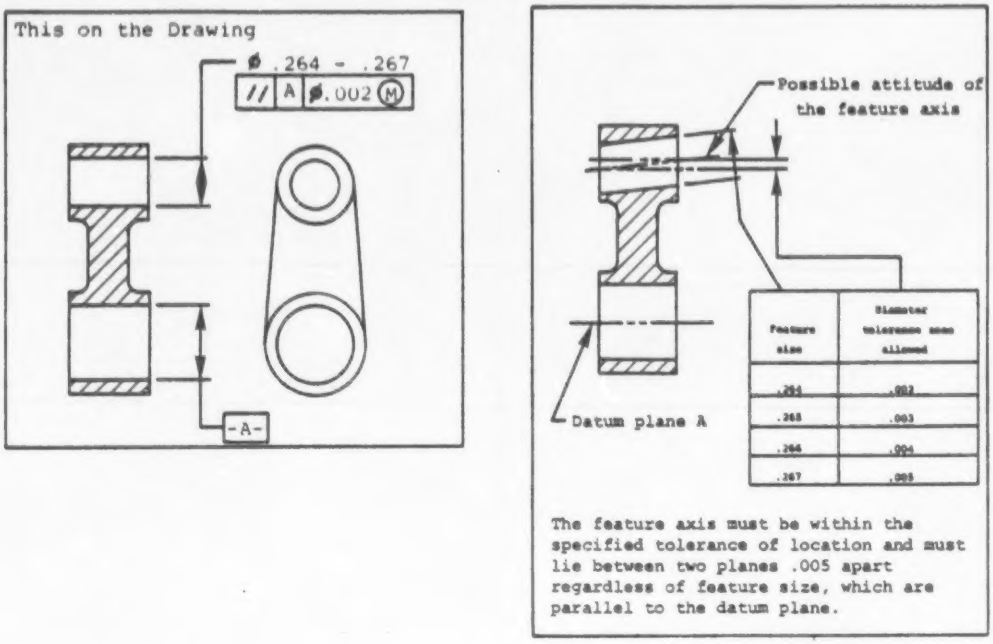
The surface must be within the specified tolerance of size and must lie between two planes .005 apart which are parallel to the datum plane.

Figure 27-5-17 Parallelism Form Control of a Surface (Rule #1)


This on the Drawing
// A .005
-A-
Means This
.005 wide tolerance zone
Possible attitude of the feature axis
Datum plane A

The feature axis must be within the specified tolerance of location and must lie between two planes .005 apart regardless of feature size, which are parallel to the datum plane.

Figure 27-5-18 Parallelism Form Control of an Axis (Rule #3)


This on the Drawing
ø .264 - .267
// A ø.002 Ⓜ
-A-
Possible attitude of the feature axis
Datum plane A

Feature size	Diameter tolerance zone allowed
.264	.002
.265	.003
.266	.004
.267	.005

The feature axis must be within the specified tolerance of location and must lie between two planes .005 apart regardless of feature size, which are parallel to the datum plane.

Figure 27-5-19 Parallelism Form Control with Diameter Feature Symbol (Rule #3)

Measurement of parallelism involves measuring the distance between the feature surface or axis and the datum surface or axis. Indicators or profile tracing equipment are most commonly used.

LOCATION TOLERANCES

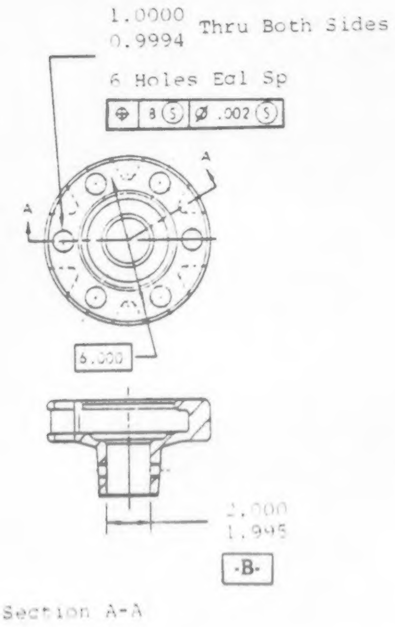
Location tolerances control position, concentricity, and symmetry (See Figure 27-5-2). These tolerances involve related features and serve to locate features as required for assembly (fit) and function. RFS or MMC applies in all cases in accordance with Rule #2.

Position

A positional tolerance defines a zone within the axis or center plane of a feature is permitted to vary from true position (theoretically exact position). Positional tolerance is normally applied to internal mating features such as holes and slots and external mating features such as shafts, bosses, lugs and tabs.

The most restrictive application of positional tolerance is the RFS basis. When RFS applies, the feature's location must be within the positional tolerance from theoretically true position regardless of feature size. This concept is illustrated in Figure 27-5-20.

DRAWING



INTERPRETATION

1. Position of the holes must be basically 60° apart ($\frac{360^\circ}{6}$) on a 6.000 diameter and within a 0.002 cylindrical tolerance zone of such basic position as measured to datum B regardless of hole actual diameter or datum B actual diameter.
2. A hole at LMC is as accurately positioned as a hole at MMC.
3. The RFS application prohibits shift in hole position with changes in the diameter of datum B, i.e., the axis of a hole is positioned in relation to the axis of datum B.

Figure 27-5-20 Positional Tolerance on an RFS Basis

When positional tolerance applies at MMC, it can be interpreted in terms of the surface of the feature or axis of the feature. This is illustrated in Figure 27-5-21 by using a hole as the example.

Positional features are measured by comparative techniques (Module 27-3) and optics or autocollimator (Module 27-4).

Concentricity

Concentricity defines a cylindrical tolerance zone within which the axes of all cross-sectional elements of a feature's surface of revolution must lie with respect to the axis of a datum feature. As with all location tolerances, RFS or MMC is specified by the drawing in accordance with Rule #2. Concentricity is normally measured by comparative techniques (Module 27-3). A typical application is illustrated in Figure 27-5-22.

Symmetry

Symmetry defines two parallel planes separated by the symmetry tolerance and equally disposed about the center plane of the datum within which the center plane of the feature must lie. Symmetry is illustrated in Figure 27-5-23. It is measured with the same techniques as for position.

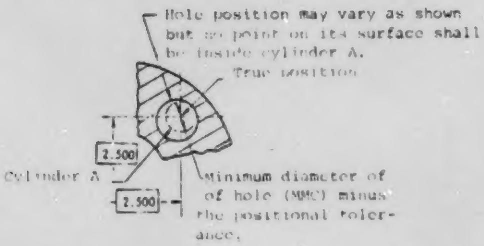
Runout

Runout is a composite tolerance used to control the functional relationship of features to a datum axis. Such features are those constructed around or at right angles to a datum axis.

⌖	⌀.xxx Ⓜ

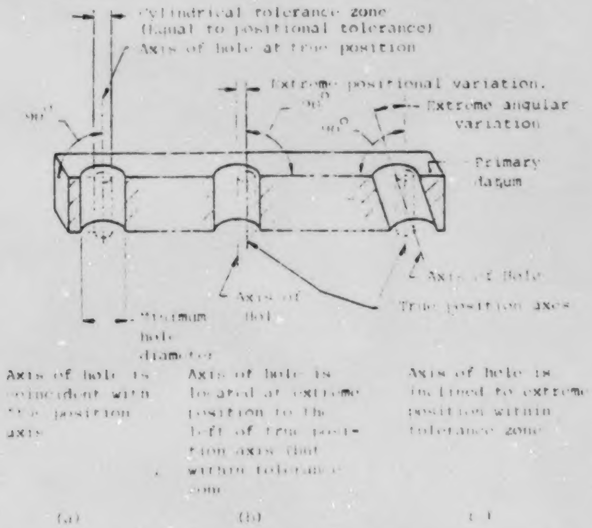
Means:

1. In terms of the cylindrical surface of the hole:


Hole position may vary as shown but no point on its surface shall be inside cylinder A.
True position
2.500
Cylinder A
2.500
Minimum diameter of of hole (MMC) minus the positional tolerance.

No element of the hole surface can be inside a theoretical cylinder, located at true position, having a diameter equal to that of Cylinder A (MCC feature diameter minus the positional tolerance).

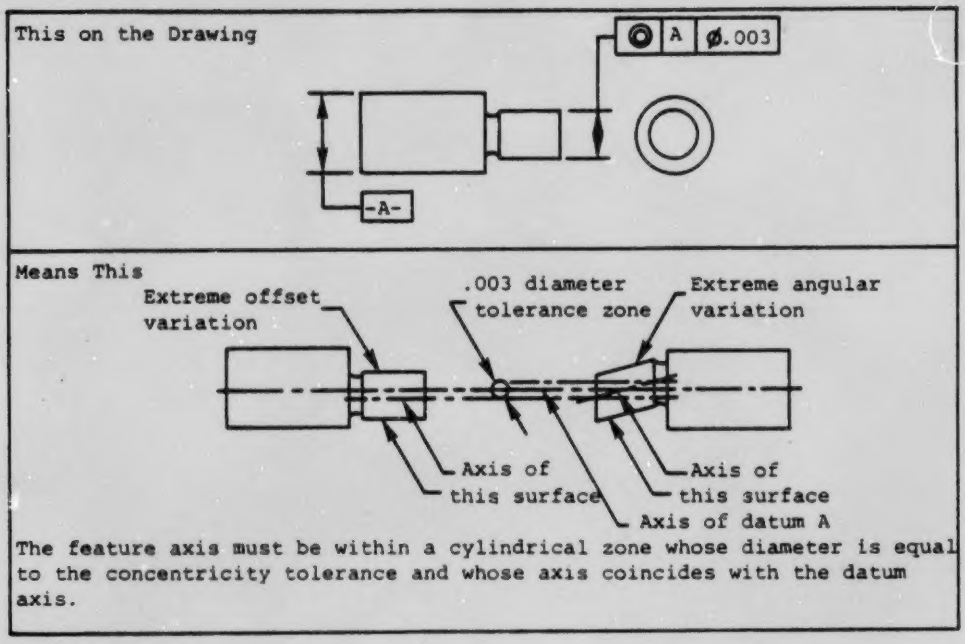
2. In terms of the axis of the hole:


Cylindrical tolerance zone (Equal to positional tolerance)
Axis of hole at true position
Extreme positional variation.
90°
90°
90°
Extreme angular variation
Primary datum
Axis of Hole
Axis of hole
True position axes
Minimum hole diameter
Axis of hole is coincident with true position axis
Axis of hole is located at extreme position to the left of true position axis within tolerance zone
Axis of hole is inclined to extreme position within tolerance zone
(a)
(b)
(c)

Note that the length of the tolerance zone is equal to the length of the feature, unless otherwise specified on the drawing.

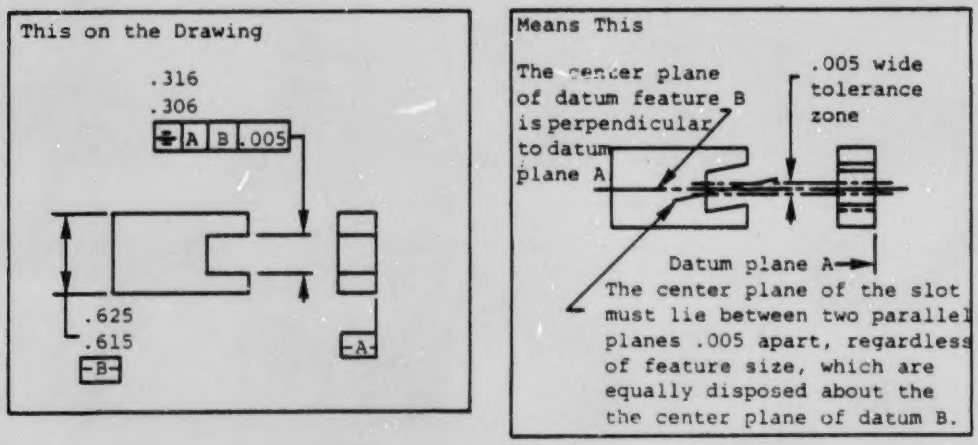
The axis of the hole must fall within a cylindrical tolerance zone whose axis is located at true position and having a diameter equal to the positional tolerance. Such diameter increases as the feature diameter departs from MMC.

Figure 27-5-21 Positional Tolerance on an MMC Basis


This on the Drawing
A
ø.003
-A-
Means This
Extreme offset variation
.003 diameter tolerance zone
Extreme angular variation
Axis of this surface
Axis of this surface
Axis of datum A

The feature axis must be within a cylindrical zone whose diameter is equal to the concentricity tolerance and whose axis coincides with the datum axis.

Figure 27-5-22 Concentricity Location Control (RFS)

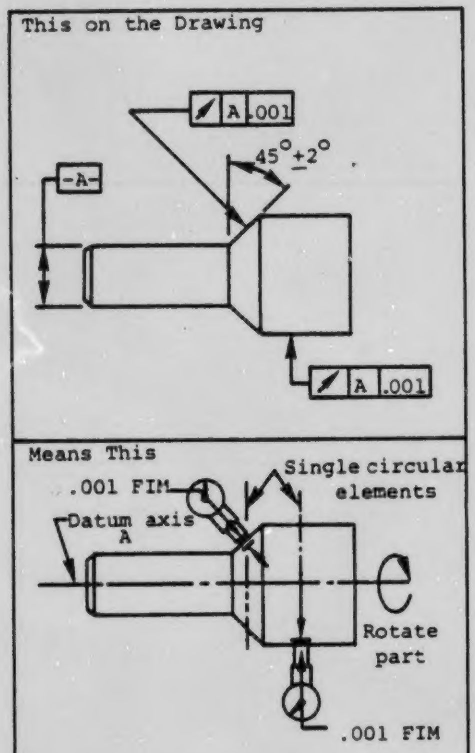

This on the Drawing
.316
.306
A
B
.005
.625
.615
-B-
-A-
Means This
The center plane of datum feature B is perpendicular to datum plane A
.005 wide tolerance zone
Datum plane A

The center plane of the slot must lie between two parallel planes .005 apart, regardless of feature size, which are equally disposed about the the center plane of datum B.

Figure 27-5-23 Symmetry Location Control (RFS)

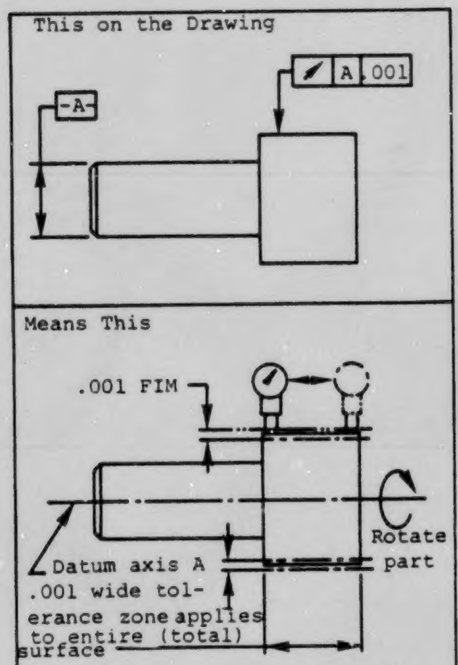
Runout is measured by comparative indicators (See Module 27-3), such that the maximum detected variation is compared with the runout tolerance to determine acceptance. Thus, "full indicator movement (FIM)" constitutes the measured value. (NOTE: prior texts may use such terms as full indicator reading (FIR) or total indicator reading (TIR); these former terms have identical meaning as FIM.

There are two types of runout control: circular and total. Where total applies the word TOTAL must be beneath the runout control symbol. Circular and total runout is illustrated in Figure 27-5-24 and Figure 27-5-25 respectively. As illustrated, Rule #1 applies to runout. (Please refer to the next page for Figures 27-5-24 and 27-5-25).


This on the Drawing
A .001
45° ±2°
-A-
A .001
Means This
.001 FIM
Single circular elements
Datum axis A
Rotate part
.001 FIM

The features must be within the specified tolerance of size. At any measuring position, each circular element of these surfaces must be within the specified runout tolerance (.001 full indicator movement) when the part is rotated 360° about the datum-axis with the indicator fixed in a position normal to the true geometric surface. (This does not control the profile elements of these surfaces. Only the circular elements are controlled.) Whether the indicator is oriented normal to the actual surface or the true geometric (theoretically exact) surface will cause only a slight "cosine error" change in the magnitude of the FIM reading.

Figure 27-5-24 Circular Runout


This on the Drawing
-A-
A .001
Means This
.001 FIM
Rotate part
Datum axis A
.001 wide tolerance zone applies to entire (total) surface

The feature must be within the specified tolerance of size. The entire surface must lie within the specified runout tolerance zone (.001 full indicator movement) when the part is rotated 360° about the datum axis with the indicator placed at every location along the surface in a position normal to the true geometric surface, without reset of the indicator. (This controls the cumulative profile and circular elements of the entire surface). Whether the indicator is oriented normal to the actual surface or the true geometric (theoretically exact) surface will cause only a slight "cosine error" change in the magnitude of the FIM reading.

Figure 27-5-25 Total Runout

EXERCISES

Obtain engineering drawings for mechanial components or systems and using these drawings as a reference discuss or answer the following:

1. Are the dimensions recorded on the drawings given to the same number of decimal places as the actual physical measurement? Briefly discuss your answer.
2. List and briefly discuss four tolerancing methods. Are there examples of these on your drawings? If so give an example of each tolerancing method.
3. Show how the dimension 1.6526 inches could be rounded off to:
   a. four decimals
   b. three decimals
   c. two decimals
   d. one decimal
   e. a whole number
4. Discuss the applicable rule for the case which applies to drawings giving size limits but not form or location controls.
5. Discuss the rule which applies to the form controls which are applicable to the axis of the feature.
6. Discuss the rule applying to a drawing giving location controls.
7. Discuss the rule(s) applying to the following form tolerances:
   a. Straightness
   b. Flatness
   c. Roundness
   d. Cylindricity
   e. Angularity
   f. Perpendicularity
   g. Parallelism

8. Discuss the rule(s) applying to the following location tolerances:
   a. Position
   b. Concentricity
   c. Symmetry
9. Runout is a composite tolerance applicable to related features. Discuss the rule which applies to this tolerance.
10. To reinforce the dimensional tolerances discussed in this module, perform measurements for parallelism, angularity and flatness described in the Procedures section.

MATERIALS

1. Test indicator
2. Weight stand
3. Surface plate
4. Sine bar
5. Autocollimator and optical targets
6. Gage blocks
7. Parallel bar

PROCEDURES

1. Measure the parallelism of either a gage block or parallel bar using a test indicator, height stand and surface plate.
2. Measure angularity of arc angle block using a sine bar and test indicator.
3. Measure the flatness of a surface plate using an autocollimator and optical targets.

DATA TABLE

None.

REFERENCE MATERIALS

ANSI Y14.5-1973, American Society of Mechanical Engineers, Dimensioning and Tolerancing, American Society of Mechanical Engineers, 1973.

Society of Manufacturing Engineers (SME), Handbook of Industrial Metrology, Prentice-Hall, Inc., 1967.

Farago, Francis T., PhD, Handbook of Dimensional Measurement, Industrial Press Inc., Third Printing, 1968.

Technical Committee ISO/TC 12, ISO 1000, American National Standards Institute, 1973.

TEST

Read each questions carefully. Be sure to provide the specific information each question requires. Make your answer brief. Use the backs of the test if you need more space.

1. Define the following terms:
   a. maximum material condition
   b. least material condition
   c. regardless of feature size
   d. flatness
   e. cylindricity
   f. parallelism
   g. true position

h. concentricity ____

____

____

____

2. Identify the following tolerance as limit, unilaterial or bilaterial:

a. 5.248 - 5.252

b. $1.125\,^{+0.000}_{-0.005}$

c. 125.72 ±0.05

3. Round the following to the specified number of decimal places:

a. 12.1458 to one decimal place

b. 1.5552 to two decimal places

c. 3.7445 to three decimal places

4. - 15. Match the geometric characteristic with its symbol by placing the letter of the characteristic in the right hand column adjacent to the symbol in the left hand column:

_____4. ⏤ (a) angularity
_____5. ⏥ (b) concentricity
_____6. ○ (c) cylindricity
_____7. ↗ (d) flatness
_____8. ⌭ (e) parallelism
_____9. ⌯ (f) perpendicularity
_____10. ⌒ (g) position
_____11. ◎ (h) profile of a line
_____12. ∠ (i) roundness
_____13. ⌖ (j) runout
_____14. ⊥ (k) straightness
_____15. // (l) symmetry

16. State the meaning of the following feature control symbols:

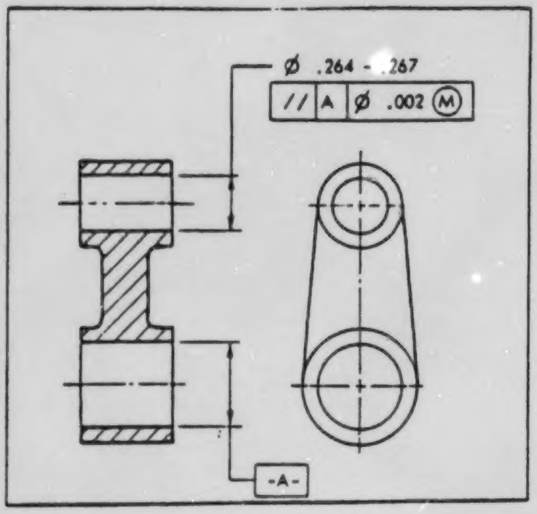
a.

↗	B	.001

b.

⌖	A	.005 Ⓜ

Use the following sketch in answering questions 17 and 18.



17. If the feature size in the above sketch is .264 inch what is the tolerance on the geometrical relationship of the feature's axis with datum A?

____

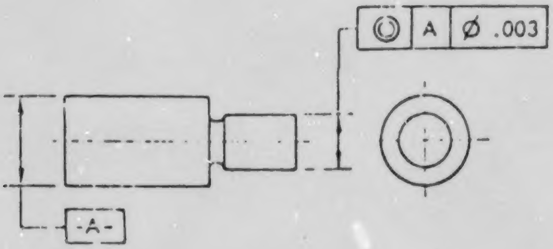
____

18. If the feature size in the above sketch is .266 what is the tolerance on the geometrical relationship of the feature's axis with datum A?

____

____

19. If the feature size in the following sketch is .502, what is the tolerance of the geometrical relationship of the axis of the feature with datum A?



20. When a perpendicularity tolerance is specified for an axis, Rule #3 applies. Describe how an inspector would know from the feature control symbol if such a tolerance applies on an RFS or MMC basis.

21. When a position tolerance is specified for a feature, Rule #2 applies. Describe how an inspector would know from the feature control symbol if such a tolerance applies on an RFS or MMC basis.

APPENDIX A

APPENDIX A
GLOSSARY

This glossary is a quick reference for terms and definitions and should be referred to whenever new terms are encountered.

- Actual Size - An actual size is the measured size of the feature.
- Angularity - Angularity is the condition of a surface, axis, or center plane which is at a specified angle (other than 90°) from a datum plane or axis. Symbol: ∠
- Basic Dimension - A dimensional specified on a drawing as BASIC (or abbreviated BSC) is a theoretical value used to describe the exact size, shape, or location of a feature. It is used as the basis from which permissible variations are established by tolerances on other dimensions or notes. A basic dimension can be symbolized by boxing it: ▭
- Basic Size - The basic size is that size from which limits of size are derived by the application of allowances and tolerances.
- Bilaterial Tolerancing - A bilaterial tolerance is a tolerance in which variation is permitted in both directions from the specified dimension.
- Center Plane - Center plane is the middle or median plane of a feature.
- Circularity - See Roundness.
- Concentricity - Concentricity is a condition in which two or more features (cylinders, cones, spheres, hexagons, etc.) in any combination have a common axis. Symbol: ◎

- Cylindricity - Cylindricity is a condition of a surface of revolution in which all points of the surface are equidistant from a common axis. Symbol: ⌭

- Datum - Datums are points, lines, planes, cylinders, axes, etc., assumed to be exact for purposes of computation, from which the location or geometric relationship (form) of features of a part may be established.
- Datum Identification Symbol - The datum identification symbol contains the datum reference letter in a drawn rectangular box, e.g., [-C-]
- Datum Target - A datum target is a specified datum point, line, or area identified on the drawing with a datum target symbol ⊕ used to establish datum points, lines, planes, or areas of special function, or manufacturing and inspection repeatability.
- Dimension - A dimension is a numerical value expressed in appropriate units of measure and indicated on a drawing along with lines, symbols, and notes to define the geometrical characteristics of an object.
- Feature - A feature is component portion of a part that can be used as the basis for a datum.
- Feature Control Symbol - The feature control symbol is a rectangular box containing the geometric characteristics symbol and the form or location tolerance. If necessary, datum references and modifiers applicable to the feature or the datums are also contained in the box e.g., [// A .005]
- Fit - Fit is the general term used to signify the range of the tightness or looseness which may result from the application of a specific combination of

allowances and tolerance in the design of mating part features. Fits are of four general types: clearance, interference, transition, and line.

- Flatness - Flatness is the condition of a surface having all elements in one plane. Symbol: ▱
- Form Tolerance - A form tolerance states how far actual surfaces or features are permitted to vary from the desired form implied by the drawing. Expressions of these tolerances refer to flatness, straightness, parallelism, perpendicularity, angularity, roundness, cylindricity, runout, profile of any surface, and profile of any line.
- Full Indicator Movement (FIM) - Full indicator movement is the total indicator movement observed with the dial indicator in contact with the part feature surface during one full revolution of the part about its datum axis. Full indicator movement also refers to the total indicator movement observed while in traverse over a fixed noncircular shape.
- Geometric Characteristics - Geometric characteristics refer to the basic elements or building blocks which form the language of geometric dimensioning and tolerancing. Generally, it refers to the symbols used in both form and location tolerancing.
- Least Material Condition - The condition where a feature of size contains the least amount of material within the stated limits of size, e.g., largest hole size and smallest shaft size.
- Limits of Size - The limits of size are the applicable maximum and minimum sizes of a feature.
- Location Tolerance - A location tolerance states how far individual features may vary from the perfect location implied by the drawing. Expressions of

these tolerances normally refer to position, concentricity, and symmetry.

- Maximum Material Condition (MMC) - The condition where a feature size contains the maximum amount of material within the stated limits of size, e.g., minimum hole size and a maximum shaft size. Symbol: Ⓜ
- Median Plane - Median plane is the middle or center plane of a feature.
- Minimum Material Condition - See Least Material Condition.
- Modifier - A modifier is the term used to describe the application of the maximum material condition or "regardless of feature size" principles. The modifiers are maximum material condition (MMC). symbol Ⓜ, and regardless of feature size (RFS), symbol Ⓢ.
- Normality - See Perpendicularity.
- Parallelism - Parallelism is the condition of a surface, line, or axis which is equidistant at all points from a datum plane or axis. Symbol: //
- Perpendicularity - Perpendicularity is the condition of a surface, axis, or line which is 90° from a datum plane or a datum axis. Symbol: ⊥
- Positional Tolerance - The permissible variation of a feature from the true position. Symbol: ⌖
- Profile of Any Line - Profile of any line is the condition permitting a uniform amount of profile variation, either unilaterally or bilaterally, along a line element of a feature. Symbol: ⌒
- Profile of Any Surface - Profile of any surface is the condition permitting a uniform amount of profile variation, either unilaterally or bilaterlaly, on a surface. Symbol: ⌓

- Projected Tolerance Zone - A projected tolerance zone is a tolerance zone applied to a hole in which a pin, stud, screw, or bolt, etc., is to be inserted. It controls the perpendicularity of the hole to the extent of the projection from the hole and as it relates to the mating part clearnace. The projected tolerance zone extends above the surface of the part to the functional length of the pin, screw, etc., relative to its assembly with the mating part. Symbol: Ⓟ
- Regardless of Feature Size (RFS) - This is the condition where the tolerance of form or position must be met irrespective of where the feature lies within its size tolerance. As applied to datums, it refers to the actual size of the datum feature. Symbol: Ⓢ
- Roundness - Roundness is the condition on a surface of revolution (cylinder, cone, sphere) where all points of the surface intersected by any plane (1) perpendicular to a common axis (cylinder, cone) or (2) passing through a common center (sphere) are equidistant from the axis. Symbol: ○
- Runout - Runout is the deviation from the desired form of a part surface of revolution detected during full rotation of the part on a datum axis when using a dial indicator (or equivalent measuring device). Symbol: ↗ Circular Runout: ⌀ Total Total Runout
- Size Tolerance - A size tolerance states how far individual features may vary from the desired size. Size tolerances are specified with either unilateral, bilateral, or limit tolerancing methods.
- Squareness - See Perpendicularity.

- Straightness - Straightness is a condition where an element of a surface is a straight line. Symbol: —
- Symmetry - Symmetry is a condition in which a feature is symmetrically disposed about the center plane of a datum feature. Symbol: ≡
- Tolerance - A tolerance is the total amount by which a specific dimension may vary; thus, the tolerance is the difference between limits.
- True Position - True position is a term used to describe the theoretically perfect (exact) location of a point, line, or plane (normally the center) of a feature in relationship with a datum reference or other feature.
- Virtual Size - Virtual size of a feature is the effective size of the profile that must be considered. in determining the clearance between mating parts or features. It is a derived size generated from the collective effect of all profile variations permitted by the specified tolerances. It represents the most extreme condition of assembly at MMC.

NUCLEAR TECHNOLOGY

MODULE 27 - 6

CALIBRATION

COURSE 27: METROLOGY

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 27 METROLOGY

MODULE 27-1	Fundamentals of Metrology
MODULE 27-2	Fixed Gages, Dividers, Calipers and Micrometers
MODULE 27-3	Gage Blocks, Mechanical Comparators and Electronic Comparators
MODULE 27-4	Angle Measurement Instruments, Optical Projectors and Surface Texture Gages
MODULE 27-5	Tolerancing
⇨ MODULE 27-6	Calibration
MODULE 27-7	Statistical Techniques in Metrology
MODULE 27-8	The Total Measurement System

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INTRODUCTION

Prior modules of this course have described a number of measuring instruments and their applications. Such measuring instruments are not suitable for inspection of product unless they are calibrated. Through the process of calibration, the accuracy of each measuring instrument is maintained within established limits thusly making the instruments suitable for inspection functions.

One can view the role of calibration from the buyer's viewpoint or the seller's viewpoint. From the buyer's point of view, the major role of calibration is to ensure acceptance inspection measuring devices are sufficiently accurate. This outlook is focused toward ensuring final product conforms with specified requirements. From the seller's viewpoint, it is equally important to ensure that each manufacturing step has sufficient accuracy to produce a product which will conform to specified requirements. Since nonconforming product always means extra costs, the buyer's and seller's views tend to agree on the need for accurate in-process measuring instruments to avoid extra costs. In most cases, government regulations approach calibration from the buyer's viewpoint.

If only the buyer's parochial view toward acceptance inspection is considered, the calibration program would include only those measuring devices used to determine if final product conforms with specified requirements. The seller's point of view adds to the calibration program those measuring devices used to establish the accuracy of discrete manufacturing steps. Therefore, many organizations include all measuring devices in their calibration program whether the instruments are used by manufacturing personnel or QA/QC inspectors.

This module describes the principles on which calibration programs are developed no matter which instruments are included in the calibration program. The module then describes the key elements of a calibration program based on these principles. Finally, exercises are suggested for students/trainees to prepare calibration procedures and perform calibrations of selected instruments. Both of these functions may be performed or reviewed by the QA/QC Technician.

MODULE PREREQUISITES

The student/trainee shall have completed all previous modules of this course.

OBJECTIVES

Upon completion of this module, the student/trainee shall be able to do the following:

1. Define the terms calibration, traceability, national standard, reference standard, and out-of-calibration.
2. Describe the role of the U.S. National Bureau of Standards with respect to calibration.
3. State the principle and describe its role in the calibration program associated with each of the following:
    - a. Tolerance-to-Accuracy Ratio
    - b. Traceability
    - c. Accuracy of Calibration
    - d. Interval of Calibration

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4. Given any of the ten elements of a calibration program, briefly describe its contribution to the calibration program.
5. Name four sources which may independently cause an instrument to be out-of-calibration.
6. Name any two methods of adjusting calibration intervals and briefly describe the key features of each.
7. Given a type of record used in the calibration program, state the purpose of the record and describe its use.
8. Demonstrate the ability to verify the adequacy of calibrations by either performing calibrations or evaluating calibrations performed by others.

NOTES TO INSTRUCTOR / STUDENT

Laboratory exercises are recommended to develop student/trainee skills in development of written procedures describing a calibration program and in performing basic calibration. This module includes suggested exercises of this purpose although the instructor will need to tailor these to local circumstances. Advance preparation will be necessary for:

1. Determining if a tour of a commercial calibration laboratory will be included.
2. Selection of instruments to be calibrated.
3. Selection of standards and measuring instruments to be used in the calibration procedure.

SUBJECT MATTER

TERMINOLOGY

Many of the terms used throughout industry and government with respect to standards and calibration lack universally accepted definitions. This is particularly evident with descriptive terms for standards such as "qualified", "basic", "fundamental", and "absolute". Therefore, the QA/QC Technician must be alert for the meaning of terms as intended by the author of literature on calibration.

- Calibration - The comparison of an instrument with a reference standard or with an instrument of equal or closer tolerance to detect and quantify inaccuracies and to report or eliminate those inaccuracies.
- Traceability - The ability to trace the calibration of an instrument and/or standard to the national standard or to accepted physical constants.
- National Standard - The embodiment of the unit of measurement either physically or by procedural technique as maintained by the U.S. National Bureau of Standards.
- Adjustment - The manipulation of adjustable features of an instrument to bring the instrument's accuracy and/or precision closer to the corresponding values of the standard.
- Repair - The replacement of parts of an instrument to bring the instrument's accuracy and/or precision closer to the corresponding values of the standard.
- Reference Standards - The primary, secondary and working standards which are used in a calibration program and which establish the basic accuracy limits for that program.

- Uncalibrated Instrument - An instrument or standard that is not subject to the calibration program. (This term is used by some to mean an instrument past due for calibration and by others to mean an instrument which is out of calibration. See Calibration Not Required.)
- Out of Calibration - An instrument or standard found at calibration to have accuracy outside the specified accuracy limit. (This term is used by some to mean an instrument which is overdue for calibration).
- Overdue or Delinquent Instrument - An instrument or standard subject to the caibration program but is presently overdue for recalibration. (NOTE: a deliquent instrument is not necessarily out of calibration; its accuracy is considered unknown until it is recalibrated.)
- Calibration Not Required - An instrument or standard which is not required to be calibrated. (Basis must be documented.)

ROLE OF U.S. NATIONAL BUREAU OF STANDARDS

Module 27-1 describes units of measurement and the role of the U.S. National Bureau of Standards with respect to maintaining either test procedures or physical specimens which embody the unit of measurement. Such test procedures or physical specimens serve as the national standard to which all calibrated measuring instruments in the United States are traceable. The final step in traceability is achieved by the calibration services offered by the U.S. National Bureau of Standards. These calibration services are offered at a fee and are limited to the highest order of reference standards used by industry and other government agencies. (See Hierarchy of Standards, Module 27-1.)

PRINCIPLES OF OPERATION

The inspection process involves a triad of disciplines. First, the designer stipulates on drawings the sizes, forms and positions to be met by the manufacturing processes. Secondly, the inspection activity determines the acceptance of the manufactured items to the designer's requirements through the use of calibrated measuring instruments. Thirdly, the calibration of measuring instruments is traceable to a national standard. Regardless of which organization designed, manufactured, or inspected the product and regardless of which organization calibrated the measuring instruments and reference standards uniformity of results is necessary to ensure fit, function and interchangeability of product. Such uniformity is possible by the application of principles associated with tolerance-to-accuracy ratio, traceability, accuracy of calibration, and intervals of calibration.

Tolerance-to-Accuracy Ratio

The capability of an instrument and its accuracy determine if it is suitable for use in a given measurement or calibration process. The tolerance of the feature to be measured can dictate the type of instrument to be selected and demand certain accuracy of the instrument. For example, a tolerance of ±.005 inch demands more accuracy than a tolerance of ±.050 inch. If the accuracy of instruments are known, selection of an instrument for use is based on the tolerance of the feature to be measured. The principle of selecting an instrument that gives a 4 to 1 (or 10 to 1) tolerance-to-accuracy ratio ensures use of a sufficiently accurate instrument.

Traceability

The demands of competitive industry and, in some cases, federal or state laws require traceability of measuring instruments. The principle of every measuring instrument and standard having traceability regardless of the number of intermediate calibration steps ensures that the accuracy of every instrument or standard is ultimately based upon the same value, i.e., the national standard or accepted physical constants. Such traceability involving a commerical calibration laboratory is illustrated in Figure 27-6-1. If any link in the calibration chain is broken, the ultimate accuracy embodied in the national standard is not reflected in the measurement of the part; hence, the need for traceability.

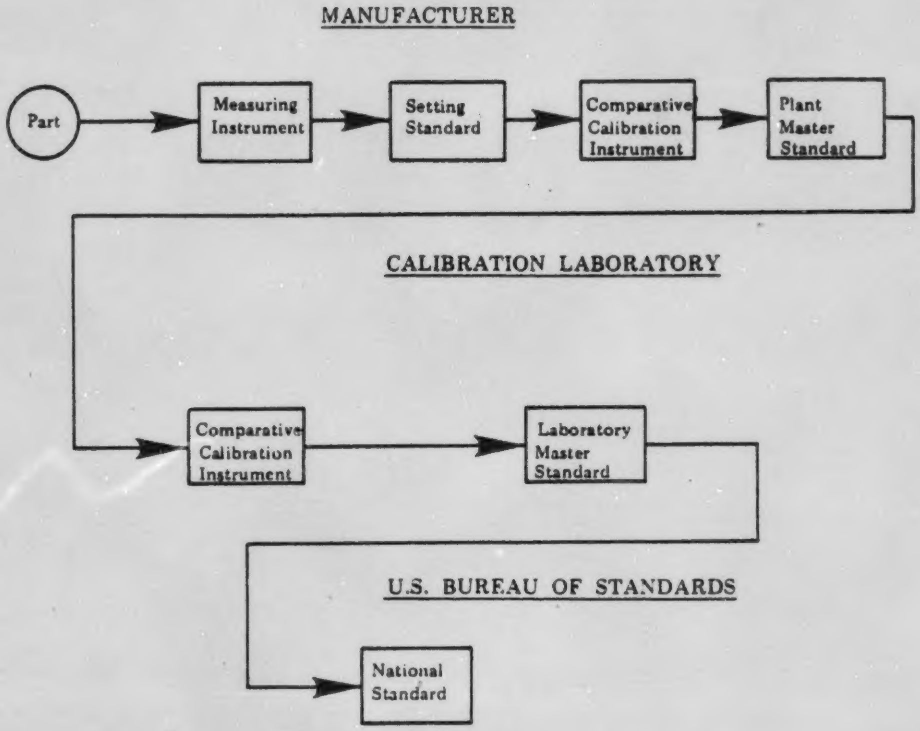

MANUFACTURER
Part
Measuring Instrument
Setting Standard
Comparative Calibration Instrument
Plant Master Standard
CALIBRATION LABORATORY
Comparative Calibration Instrument
Laboratory Master Standard
U.S. BUREAU OF STANDARDS
National Standard

Figure 27-6-1 Traceability

Accuracy of Calibration

Controversy quickly erupts whenever discussions arise on "required" accuracy of calibration. This is because few types of instruments have calibration accuracies defined by national standards. Also, there is not agreement on the need to establish national standards for calibration of many instruments.

Calibration accuracy limits are established for certain measuring instruments and standards. For example, ANSI B 89.1 establishes accuracies of the various grades of gage blocks. ANSI B1.2 establishes accuracies of gaging for the inspection of unified screw threads. However, these standards do not give requirements for the calibration of the instrument used to test the accuracy of the gage block or the thread gages.

Gages having many applications are not generally subject to a national standard. Examples of such gages are micrometers, vernier calipers, dial indicators, test indicators, electronic comparators, optical projectors, and engineering microscopes. Nonetheless, literature on the "recommended" accuracies of calibration of these instruments is published by several sources including U.S. National Bureau of Standards, manufacturers of such instruments, research institutions, and individual's articles in technical periodicals.

Chaos does not (or should not) result from a lack of national standards on calibration accuracies. This is because the capability and intended use of the item to be calibrated dictates the calibration accuracy. Each company establishes calibration accuracies for each type of measuring equipment and defines these accuracies in the calibration procedures. The principle for calibration accuracy of dimensional inspection instruments is that each instrument is corrected at calibration to be accurate to a defined value. This establishes the accuracy of quality level for measurements and tests. Application of this principle for the instruments listed in Figure 27-6-1 is illustrated in Table 27-6-1. Practical limits are imposed by "state-of-the-art" calibration techniques.

The correction of an instrument's accuracy at calibration may be accomplished by adjustment, repair, or correction curves. Instruments which do not lend themselves to adjustment or repair can still be used if correction curves are developed. These curves plot known error against range. The error value of the size being measures is used to correct the measurement result.

Table 27-6-1

Calibration Accuracy for Part Tolerance of 0.010

Instruments Listed in Figure 27-6-1	Calibration Accuracy	
	Ten-to-One Rule	Four-to-One Rule
Measuring Instrument	0.001	0.0025
Setting Standard	0.0001	0.000625
Calibration Instrument	0.00001	0.000156
Plant Master Standard	0.000001	0.000039
Laboratory Calibration Instrument	0.000001*	0.0000098
Laboratory Master Standard	0.000001*	0.0000024
National Standard	0.000001*	0.000001*

*Practical state-of-the-art limit for dimensional measurement is ± 0.000001 inch.

Intervals of Calibration

Once an instrument is calibrated, it tends to lose accuracy with time and use. Calibration is repeated at periodic intervals to maintain the accuracy of the instrument. Methods of determining such time intervals are described later in this module. The principle is stated as intervals of calibration are selected such that a high probability exists that instruments are recalibrated prior to the accuracy of the instrument exceeding its designated limit. The probability value is dependent on a company's policy. This principle provides for assurance within the probability value that instruments are accurate to defined limits at any time of their use.

ELEMENTS OF THE CALIBRATION PROGRAM

Each organization is faced with establishing a calibration program for the measuring devices on hand and for each new instrument when purchased. Whether the organization provides its own calibration laboratory or contracts for services by a commercial calibration laboratory, a documented calibration program is established to ensure that suitability accurate instruments are made available to inspection and test activities. Elements of the documented program are summarized as follows and more fully described in subsequent pages:

- Equipment Identification - Each measuring and test instrument and reference standard is uniquely identified by a serial number and assigned location.
- Calibration Procedures - Written procedures provide instruction on techniques used for calibrating each instrument.

- Intervals of Calibration - Specific time intervals are established for the recalibration of instruments.
- Recall Procedures - Positive means are established for recalling instruments which are due for calibration.
- Traceability - The methods of demonstrating traceability are established.
- Precalibration Checks - Accuracy of used equipment is checked prior to adjustment or maintenance.
- Labeling - The calibration status of instruments is clearly identified.
- Nonconformance - Practices are established for the identification and correction of nonconformances.
- Environmental Controls - Necessary environmental controls are established.
- Records - The specific records to be maintained are defined.

Equipment Identification

Each measuring device and standard is serialized to permit traceability of each. The serialization must avoid assignment of duplicate serial numbers such that any instrument is identifiable by its unique number.

Serialization schemes vary from company to company. Some use alpha-numeric serialization and other use only numeric serialization. Some incorporate manufacturer's serial numbers and assign local serial numbers only to those gages which are not serialized by the manufacturer. As long as each instrument has its own unique serial number, the scheme selected should work. However, as the number of instruments and standards increases, as well planned serialization scheme becomes increasingly important. Where thousands of instruments and standards are to be controlled, a nine-digit serialization scheme finds widespread use. It has the advantage of encompassing up to 999 identical instruments and completely identifying each instrument solely by the serial number. Such a scheme is illustrated in Figure 27-6-2.

	Type of Instrument	Range or Number of Pieces in the set	Consecutive Number
Serial Number:	**XXX**	**XXX**	**XXX**

Example where 265 is assigned for outside micrometers.

265 001 412 means:

265 identifies the instrument as an outside micrometer

001 identifies an 0-1 inch range

412 identifies it as the 412th. outside micrometer of this range

Example where 085 is assigned to gage block sets.

085 035 002 means:

085 identifies the instrument as a gage block set

035 identifies it as a 35 piece set

002 identifies it as the 2nd. such set

Figure 27-6-2 Nine Digit Serialization Scheme

Assignment of the first three digits of the nine digit serialization scheme is normally accomplished from an alphabetical listing of each type of instrument. Once the alphabetical listing is made, a three digit number is assigned for each type. Where there is possibility of purchasing additional types or of exceeding 999 of a single type, appropriate numbers are reserved (unassigned) to permit later addition.

Engraving is the best method of placing serial numbers on instruments. Die stamping can easily cause damage. Vibrotooling may cause damage and does not provide for best legibility. Chemical etching carries the risk of unintentionally etching gaging surfaces and causing localized corrosion. In any event, serial numbers are always applied to non-gaging surfaces. For gage blocks and for instruments too small to accommodate a serial number, the number is applied to the instrument's case.

Location of equipment is recorded to provide for easy retrieval of the equipment for calibration or other purposes. Equipment is typically assigned to calibration rooms and tool rooms and then logged in and out of these locations by the users of the equipment.

Calibration Procedures

Calibration procedures ensure consistency of calibration with least laboratory error. (See Error Sources, Module 27-1.)

A calibration procedure is prepared for each type of instrument and standard. Leaving calibration techniques to the judgment of the calibration technician has a high probability of allowing errors due to different techniques among technicians and the likelihood of omitting some features of the instrument from the calibration tests. To guard against such errors, each calibration procedure should identify:

- applicable standards and measuring instruments
- features of the instrument (or standard) to be tested at calibration
- accuracy limits for each feature
- instruction for testing each feature

Using an outside micrometer as an example, the calibration procedure may specify the standard as a 2.0 accuracy grade gage block set at the measuring instruments as optical flat and electronic height set. The features to be tested include size measurement accuracy, flatness and parallelism of anvil and spindle face, and axial and radial play of the spindle. Accuracy limits may be 0.0001 for size measurements, 0.000010 for flatness and parallelism and 0.0001 for axial play and for radial play. The instructions would delineate measurement of gage blocks selected to represent a value in each quarter-range, use of optical flat and monochromatic light to measure flatness and parallelism, and measurement of axial and radial play with the electronic height gage.

Irrespective of the instrument to be calibrated, each calibration procedure typically includes the elements listed in Table 27-6-2.

Intervals of Calibration

Calibration interval means the time for one calibration to the next calibration of a given instrument or standard. It is sometimes termed calibration frequency.

Calibration intervals are established on the basis of stability, purpose, degree of usage, precision, and accuracy. The exact calibration interval for a given instrument is established to ensure a definite probability of recalibrating the instrument prior to it being out of calibration. For example, a company may establish the policy of establishing

Table 27-6-2

Typical Arrangement of Calibration Procedure

Procedure Section	Purpose of Section
Title Page	Provides identity of the specific procedure by title; typically includes a unique number as well.
Introduction and Description	Identifies the instrument whose calibration is described by the procedure. Lists the instrument characteristics and calibration methods, typically in tabular form. Lists of any instrument accessories which are to be included in the calibration.
Equipment Requirements	Lists instruments, accessories, and standards necessary to perform the calibration. Typically lists minimum performance requirements which serve as the basis for selecting alternative instruments.
Preliminary Operations	Includes applicable instructions or preliminary steps prior to commencing the calibration steps. Examples include instrument connections, warm-up, set-up, and special environmental conditions.
Calibration Process	Provides step-by-step instructions for performing the calibration. Includes methods, interconnections, control settings, verifications, and use of calibration curves or charts. Identifies performance limits for each measurement or test. May include work sheets dependent upon complexity of calibration process. Provides a check list or record for recording each measurement and test.

calibration intervals such that 90% of the instruments will be within accuracy limits at calibration. As actual results deviate from the established goal, calibration intervals are lengthened or shortened as appropriate.

The National Conference of Standards Laboratories describes in their Recommended Practice #1 five general methods in use for the establishment of calibration intervals. These methods are engineering intuition, fixed interval through data, variable intervals, interval by use time, and interval by in-use testing. These methods are summarized below.

- Fixed Interval Through Engineering Intuition - This is by far the most prevalent method in use today. It requires that individuals with experience in the general subject equipment area generate an educated guess as to how long an item might be expected to remain within a specified tolerance. This method of determination usually treats the model and manufacturer as a group. It is seldom treated as a generic classification, e.g., micrometers, height gages. This method usually serves as the starting point for all other methods. It has the following advantages and disadvantages:

  Advantages
  Lowest initial expense.
  Offers short term flexibility.
  Serves small number of items well.

  Disadvantages
  Ultimate expense may be quite high through incorrect decisions.
  Requires the same individuals who made the initial decision or others equally qualified to monitor and adjust periods.

Does not yield useful substantiative data.
Does not establish relability level.

- Fixed Intervals Through Data - Using attribute data from calibration reports, decisions may be made on the magnitude of lengthening or shortening periodic intervals. There are various forms of evaluation using statistical techniques and decision criteria. The data must be meaningful in terms of instrument accuracy through normal use. For example, repaired and damaged item data are eliminated. The data from calibration is compared with guidelines such as those listed in Table 27-6-3 in order to adjust calibration intervals:

Table 27-6-3

Sample Guidelines for Adjustment of Interval Through Data

% of Instrument* Out-Of-Tolerance Incoming to Lab	Present Period Month	Change To Month	Pres. Period Mo.	Change To Month	Pres. Per. Mo.	Change To Month
25% or more	3	1	6	3	12	6
15 to 25%	3	2	6	4	12	9
10 to 15%	3	3	6	6	12	12
5 to 10%	3	4	6	9	12	18
5% or less	3	6	6	12	12	24
*Single type or generic group						

The fixed interval through data method of determination usually treats the model and manufacturer as a group. It may also be used by serial number or generic group. It has the following advantages and disadvantages:

Advantages

Establishes definite reliability level.
Yields useful substantiative data.
May be programmed for automatic data processing.

Ultimate expense should be low through supported decisions.

Serves large calibration workloads well.

Disadvantages

Initial expense is high.

Inefficient for small samples.

Chronic failing instrument is overloaded.

Requires sophisticated data acquisition and handling.

- Variable or Floating Intervals - This method treats an individual item or instrument separately in one of several ways. For example, automatic data processing or manual history records based on the established reliability criteria are used to evaluate the individual item each time it is processed and the date of next calibration is assigned. Or, without regard to history records and specific reliability criteria, each time an individual item is processed and found to be within tolerance the technician expands the next interval by a certain amount (e.g., increase by one month). If an out-of-tolerance condition is found, the subsequent period is shortened (e.g., decrease by one month). The variable or floating technique treats individual items by serial number only. It has the following advantages and disadvantages:

  Advantages

  Highly responsive to needed interval adjustments.

  By not using historical records it costs little to operate.

Disadvantages

Overlooks need for immediate technician investigation.

A smooth calibration workload is difficult to achieve.

By not using the history/reliability method a definite reliability level would not be known.

Susceptible to subjectivity of individual technician unless carefully monitored.

- Interval by Use Time - This method requires that an elapsed time indicator or usage tag be installed on the item to be calibrated. After a predetermined "on" time has been reached the instrument is submitted for calibration. This method of determination usually treats the model and manufacturer as a group. It may also be used by serial number or generic group. It has the following advantages and disadvantages:

Advantages

Frequently used equipment receives proportionally more attention than rarely used instrumentation.

Disadvantages

Usable only if the following conditions are met: Elapsed-time indicator is properly activated. Proof of usage data versus deterioration with time. Free from "off" time drift. Deterioration to be free from number of "on-off" sequences, loading, handling, etc.

High initial cost.

Easy for user to tamper with, (disconnect timer or run backwards).

A smoothly controlled calibration workload is difficult to achieve.

High cost of monitoring timers and policing program.

- Interval by In-Use Testing - Critical parameters within instruments are checked frequently (daily, weekly or monthly) in their use environment using portable calibration equipment. For this, data is collected and statistically analyzed to determine need for a complete calibration of instrument parameters. This method integrates calibration into a quality control function. The in-use testing technique may treat items individually by serial number or by model-manufacturer. It has the following advantages and disadvantages:

  Advantages

  Provides any attainable reliability level desired.
  Provides useful peripheral data, both attribute and variable.
  Provides maximum availability for user.

  Disadvantages

  Not practical for geographically separated instruments.
  Requires sophisticated data acquisition and handling.
  Requires detailed management.
  Requires close inventory control to find instrument to be monitored.
  Present calibration equipment not completely suitable for portable use.

The techniques described by the foregoing are in the simplest form. With certain modifications many of the disadvantages listed might be overcome. Also, there is considerable cross-over in these techniques and portions of each may be used in constructing a satisfactory program. In any event, it should be remembered that there are five sources which may independently cause an out-of-tolerance condition:

- Improper calibration procedure.
- Improper standards or calibration equipment.
- Improperly or marginally designated instruments (items under test).
- Technician error.
- Improper calibration interval.

Therefore, the calibration interval should not be adjusted on the strength of out-of-tolerance data alone; rather, engineering investigations of all possible causes should be accomplished to assure that a change to the interval is, in fact, the proper action.

Recall Procedure

The recall procedure ensures accomplishment of calibration within the calibration interval. It is normally established through an accountability system. For companies having few instruments, the calibration laboratory technician normally possesses and is accountable for all instruments. The technician requires log out and log in of the instruments by inspectors. In this manner, the technician knows the whereabouts of each instrument and can recall them for calibration at the established intervals.

For companies having many instruments, a similar procedure is established with satellite tool rooms. The main calibration laboratory assigns instruments to various tool rooms throughout the facility. Each tool room technician in turn maintains an accountability system, such as a log in/log out system, such that an individual is accountable for any given instrument at any time.

Each tool room technician has a "tickler" system which flags instruments to be recalled each week (or each month). Such tickler systems may be master listings of calibration intervals, arrangement of instrument calibration records by due dates, wall charts, computer print-out, or other method.

Traceability

The calibration program must demonstrate a valid relationship of each calibration with the national standards or an accepted value of natural physical constants. As indicated previously in Figure 27-6-1, calibrated reference standards are used in the calibration of an instrument. Each standard is in turn calibrated until either the national standards or recognized natural physical constant is reached in the hierarchy of standards.

Calibration records provide for the documentation of traceability. The calibration record for each measuring device or standard contains sufficient entries to identify the accuracy of the device or standard and the calibration standard or physical constant used in the calibration process. These record entries include:

- reference standards (or physical constants) used to perform the calibration.
- calibration date.
- calibration facility.
- environmental conditions.
- accuracy data.

Traceability is not required for natural physical constants nor for a standard derived from traceable standards by use of physical laws.

Precalibration Checks

In addition to specific calibration procedures for each type of instrument or standard, a procedure is necessary to ensure that accuracy is checked prior to commencing the calibration process. Such a procedure requires testing the accuracy of the instrument prior to any adjustment or repair.

This permits discovery of those cases where an out-of-calibration instrument may have been used for product acceptance or in calibration processes. Also, it develops data which may be used as a basis for adjusting intervals of calibration.

Labeling

The user of an instrument or standard should be able to readily determine if calibration has occurred within the established interval. Evidence of such calibration status can be afforded by color coding, tagging or labeling.

Color coding schemes assign colors to each month and a dot of color representing the month the instrument is next due for calibration is painted on the instrument or its case.

Tagging schemes attach tags to the instrument or its case. The tags may represent the color coding scheme or may contain data entries which identify data of last calibration and due date for the next calibration.

Labels having adhesive backing are applied to the instrument or its case. The label has data entries which identify date of last calibration, name of individual who performed the last calibration, and the due date of the next calibration. Labeling is typically required provided the label does not interfere with the function of the instrument. Few instruments are so small as not to accept the label and labels are available which remain adherent and legible in the oily environment of the machine shops. The label is normally placed in a prominent position on the instrument and it is easily read.

Nonconformance

The calibration program must establish responsibilities and practices for identifying and acting on nonconformances. Such nonconformances fall into one of three general groupings:

- measuring devices or reference standards found to be out-of-calibration.
- measuring devices or reference standards found to have been improperly maintained or improperly calibrated.
- measuring devices or reference standards found to have evidence of damage.

Whenever a nonconformance is identified, the instrument or standard is promptly removed from service and an evaluation is made on the effect of such nonconformance. The evaluation determines if there is probability of product or calibrations having been incorrectly accepted because of the nonconformance. To accomplish this, the evaluation includes:

- determination of the inaccuracy of the instrument or standard.
- identification of all equipment inspected or calibrated by the nonconforming instrument or standard since the date of the last calibration of the nonconforming item. (Note: if it is known that the nonconformance was caused by damage on a known date, only the effect on equipment since occurrence of the damage is identified).
- investigation of the effect of using the nonconforming item.

The investigation of the effect of using the nonconforming item is documented and serves as the basis for accepting or retesting affected equipment. The investigation compares the known inaccuracy of the nonconforming item with its prior uses to determine if it may have caused incorrect acceptance of product or calibrations. Where such comparison is not possible, results of retesting a sample of the affected equipment may serve as a basis for concluding the exact effect. Product or calibration believed to be adversely affected by use of the nonconforming item is retested.

Environmental Controls

The calibration program includes appropriate environmental controls to prevent environmental conditions from adversely affecting the accuracy of measuring devices and reference standards. These controls apply to the transport, storage and calibration of instruments and standards. Where environmental conditions cannot be controlled as desired, appropriate correction factors are determined and used to ensure accuracy.

The exact environmental controls are dependent on the types of instruments and standards and their susceptability to functional deterioration. Table 27-6-4 lists the environmental factors which are considered and the general effect of these factors.

With respect to temperature controls, a unique condition exists within calibration rooms. Items to be calibrated which are brought in from other areas are not necessarily at the same temperature as the calibration room. These items must "soak" for a time period to permit their temperature to equalize with the temperature of the reference standard.

Records

The records which support the above elements of the calibration program are generally the master serialization listing, instrument assignment log, calibration record card, delinquent report, calibration status labels, and certifications from calibration laboratories or U.S. National Bureau of Standards.

Table 27-6-4

Environmental Factors

Factors	General Adverse Effect
Temperature	Thermal expansion and contraction, alter operation of electronic items and heat sensitive parts.
Humidity	Corrosion from excess humidity, static electricity interference from insufficient humidity, alter operation of humidity sensitive parts.
Vibration	Accuracy of measurements, stability of items containing movable parts, stability of items sensitive to shock.
Radio Frequency Interference	Alters operation of electronic equipment.
Electro-Magnetic Interference	Alters operation of electrical and electronic equipment.
Background Radiation	Alters operation of radiation detection and measurement equipment.
Dust	Contact measurement interference, static electricity, stability of movable parts.
Cleanness	Contact measurement interference, soundness of electrical connections, staging errors.
Fumes	Corrosion, alter operation of equipment.

- Master Serialization Listing - This listing provides a running inventory of instruments and standards and their assigned serial numbers. Where thousands of instruments are on hand, the company may use a computer for storing, updating, and printing the listing. The supervisor of the calibration laboratory or the chief inspector is normally responsible for maintaining the listing. Purchases of additional instruments and standards must involve the responsible person to permit updating the listing and assignment of serial numbers.
- Instrument Assignment Log - This record identifies which instruments have been assigned to whom. It serves as an accountability record. It can be a log book or special record format.
- Calibration Record Card - A calibration record card is maintained for each instrument and standard calibrated by the company's calibration laboratory. Results of initial accuracy testing is recorded on this card at each calibration. Such data gives trend information which can serve as the basis for adjusting the calibration interval. For example, if an instrument is found to be accurate without adjustment or repair for three of four consecutive quarterly calibrations, the calibration interval could be changed to semi-annually. This card is illustrated in Figure 27-6-3.
- Delinquent Report - Most companies use some means of notifying responsible persons of instruments which are past due for calibration. Such instruments should have been returned for calibration but for some reason they have not been. The notification can be any format. It can be a listing of delinquent gages sent

CALIBRATION RECORD CARD

Instrument Name: Outside Micrometer, Without Vernier

Size or Range: 2-3" **Serial Number:** 265003216

Date of Issue: 2-1-78 **Tool Room:** 6B

Accuracy Limit: ±.0005

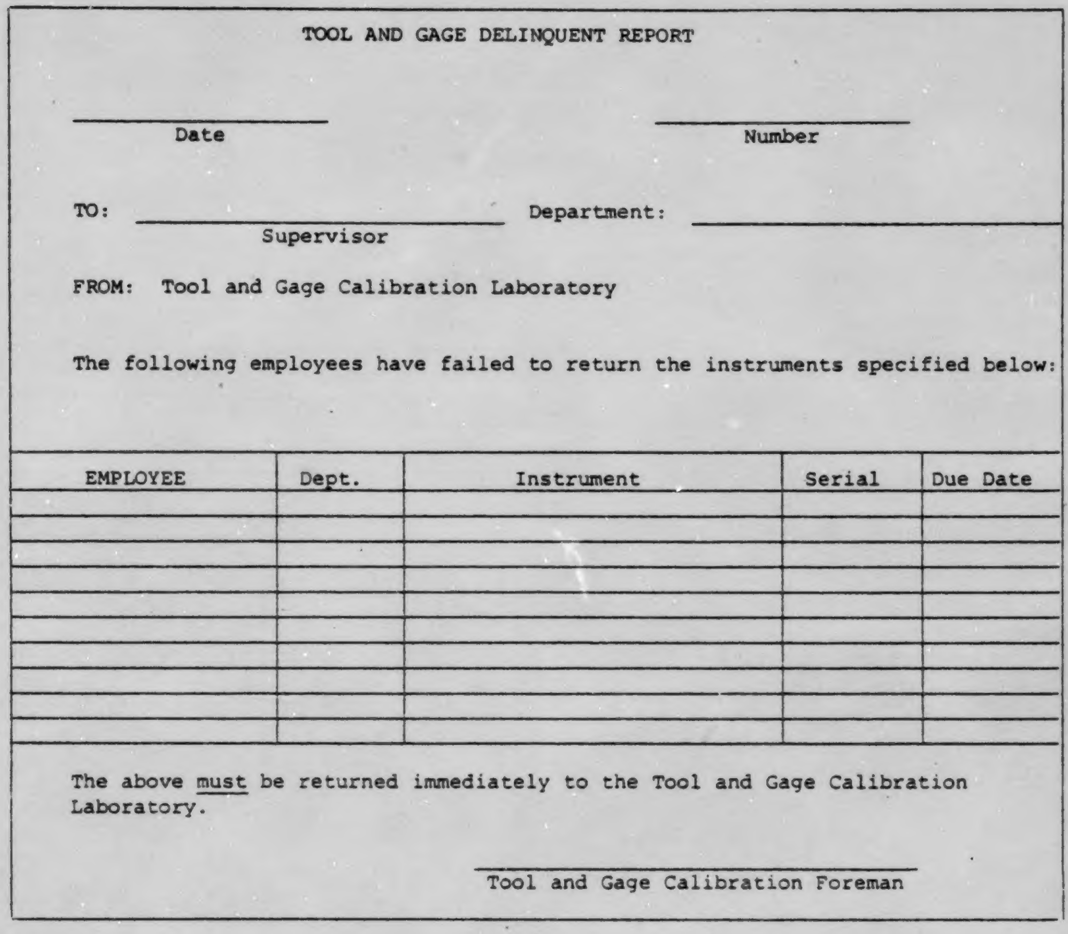
Date Of Calibration	Error For Each Quarter Range				Tested By	Adjustments and Repairs
2-1-78	0.0000	0.0000	0.0000	0.0001	JD	None
3-1-78	0.0000	0.0000	0.0000	0.0001	JD	None
4-1-78	0.0001	0.0001	0.0001	0.0001	JD	None
5-1-78	0.0001	0.0001	0.0001	0.0001	JD	None (Int. to 3 mos.)
8-1-78	0.0001	0.0002	0.0002	0.0002	JD	Reset to 0.0000
11-1-78	0.0001	0.0001	0.0001	0.0001	JD	None
2-1-79	0.0003	0.0003	0.0003	0.0003	JD	Reset to 0.0000

Use Reverse as Necessary **Form CAL-2**

Figure 27-6-3 Typical Calibration Record Card

to responsible supervisors or it can be a special form. Figure 27-6-4 illustrated a typical special form. A duplicate of each issued form is retained by the calibration technician.

- Calibration Status Label - Adhesive backed labels are widely used as the indication of calibration status. Each time the instrument is calibrated, the calibration technician removes the previous label and applies a new label. Such labels are available in a variety of sizes and materials. Labels are made from paper, cloth or aluminum. When paper or cloth labels are used in an oily environment, the calibration technician applies a thin coat of lacquer over the label to preserve the written data. Aluminum



TOOL AND GAGE DELINQUENT REPORT

____________________ Date

____________________ Number

TO: ____________________ Supervisor

Department: ____________________

FROM: Tool and Gage Calibration Laboratory

The following employees have failed to return the instruments specified below:

EMPLOYEE	Dept.	Instrument	Serial	Due Date

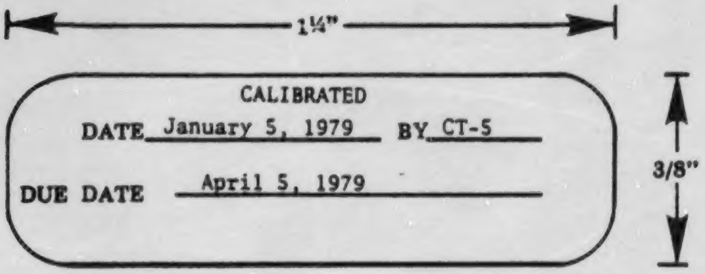
The above must be returned immediately to the Tool and Gage Calibration Laboratory.

____________________ Tool and Gage Calibration Foreman

Figure 27-6-4 Delinquent Report

labels can be read by the impression left by a ball point pen. Figure 27-6-5 illustrates a typical "calibrated" label.

Labels or tags are also used to identify rejected items pending repair or replacement. These labels or tags typically state "Rejected - DO NOT USE" and contain entries for the date of rejection, by whom, and cause of rejection.



CALIBRATED
DATE January 5, 1979 BY CT-5
DUE DATE April 5, 1979

Figure 27-6-5 Typical Status Label

- Certification from Calibration Laboratories - Instruments and standards which cannot be calibrated by the company are sent to commercial calibration laboratories. The commercial calibration laboratory provides a certification of calibration results and provides evidence of traceability of the instruments and standards used by the calibration laboratory. Module 27-3 illustrates a typical certification for gage blocks.

EXERCISES

Laboratory exercises and/or field trips to calibration laboratories are recommended. Laboratory exercises should involve the calibration of selected measuring instruments which have been used during instruction of earlier modules of this course. Guidelines for example exercises and for a field trip are given below.

Exercise #1, Preparation of Calibration Procedure

1. Preparation by Instructor:
    a. Establish working groups consisting of two to four students/trainees each.
    b. Assign to one half of the groups the task of preparing a calibration procedure for a specific instrument. (Note the Procedure section of this module cites a specific calibration procedure for a micrometer caliper. This may be used as an example.
    c. Assign to the other half of the groups the task of preparing a calibration procedure for the standard which will be employed by the first half.
    d. Earlier modules of this course should be available for review as necessary.
2. Task for Students/Trainees:
    a. Each group prepare a procedure for calibrating the assigned instrument or standard. Include the following:
        - standard and/or measuring instrument to be used
        - features to be tested
        - accuracy limits for each feature
        - instructions for testing each feature

b. Upon completion of the calibration procedures, obtain a review of the procedure by a group in the other half. Each reviewing group should determine the workability of the procedure. In addition, each review should state whether the accuracy of the standard would be adequately determined to permit its use in calibrating the instrument.

c. Select one of the procedures which appears to be best and demonstrate its use by calibrating the instrument covered by the procedure. (NOTE: additional procedures may be demonstrated as time permits). Make not if omitted, vague, and incomplete steps of the procedure are revealed by the performance of the calibration. Explain why the initial review failed to detect such weaknesses of the procedure.

Exercise #2, Evaluation of Traceability

1. Preparation by Instructor:
    a. Determine if this exercise may be accomplished locally. If the local program includes serialization and documented calibration of instrument and reference standards, the exercise can be performed locally.
    b. If this exercise cannot be performed locally, arrange for either a visit to a calibration laboratory or for review of a company's procedures. The visit or review should accomplish the tasks of step 2.
2. Tasks for Students/Trainees:
    a. Prepare a check list of items which you consider should be checked to determine if a given instrument has traceability.

b. Determine from the instructor if the evaluation is to be made of local gages, gages at a calibration laboratory or a set of procedures which describes a company's calibration program.

c. Conduct an evaluation for traceability of one gage using the check list as a guide. If procedures are being evaluated, determine if compliance with the procedure results in traceability. If gages are being evaluated, determine what evidence of traceability exists. Ensure the evaluation encompasses:
   - identification of gage
   - calibration of gage
   - identification of reference standards
   - calibration of reference standards
   - certification of accuracy to national standard or accepted physical constant

d. Prepare a report of findings. Include in the report the specific evidence of traceability. Identify any necessary evidence which is found to be nonexistant and recommend what should be done to establish necessary evidence. State your conclusion on whether traceability exists for the gage evaluated.

Exercise #3, Evaluation of Calibration Program

1. Preparation by Instructor:

   a. This exercise is structured for the students/trainees to audit the calibration program which is applied to the measuring devices used in this course.

   b. In the event a formal calibration program has not been established, this exercise could be modified to have the students/trainees assist in the development of a local calibration program.

2. Tasks for Students/Trainees:
   a. Prepare a check list of items which you consider are essential features of a calibration program. This check list will be your guide in auditing the local calibration program and it should address the ten elements described by this module.
   b. Audit the calibration program using your check list as a guide. The following sequence is suggested:
      - adequacy of procedures
      - adequacy of storage
      - adequacy of environmental controls
      - instrument identification and calibration status
      - traceability
      - compliance with calibration intervals
      - adequacy of recall practices
      - adequacy of pre-calibration checks
      - records
      - control of nonconformances
   c. Prepare a report describing the results of your evaluation. For each area where you conclude improvements are needed, state a recommendation for making the improvement and describe the basis for your recommendation. The following format is suggested:
      - Title
      - Scope
      - Personnel Contacted
      - Summary of Results
      - Specific Findings and Recommendations

Exercise #4, Verification of a Specific Calibration

1. Preparation by Instructor:
   a. This exercise provides for students/trainees to verify the adequacy of a specific calibration.
   b. To perform this exercise, students/trainees will require access to a specific instrument which has been previously calibrated, the calibration procedure, and all equipment required by the calibration procedure to perform the calibration.
2. Tasks for Students/Trainees:
   a. Obtain from the instructor the specific instruments whose calibration will be verified.
   b. Study the calibration procedure applicable to the given instrument. Determine if the procedure appears to be adequate. Consider the following and note any comment you have have:
      - clarity
      - suitability of reference standards and measuring and test equipment
      - adequacy of listing of features to be tested
      - completeness and logic of calibration steps
      - adequacy of acceptance criteria
   c. Calibrate the given instrument by explicitly following the calibration procedure. Do not use your notes on the adequacy of the procedure. As you perform the calibration, make separate notes on any difficulties encountered in performing the calibration.
   d. Compare results of your calibration with the calibration record card for the given instrument. If your results differ, repeat the calibration as necessary until you are confident of the validity of your results.

e. Determine if the calibration procedure provides for adequate calibration. This determination should be based on comparison of your two sets of notes and the results of your calibration with the calibration record for the instrument.

f. Report improvement needed in the calibration procedure and the basis thereof.

MATERIALS

Materials for exercises suggested by this module are to be selected from the material recommended by Modules 27-2, 27-3 and 27-4. If the specific procedure for calibration of a one-inch micrometer caliper is employed, the materials requirements will be as follows:

1. A one-inch micrometer caliper.
2. Gage blocks of the following size ranges:
   a. Less than 250 mils in height.
   b. In the range between 250 mils and 500 mils in height.
   c. In the range between 500 mils and 750 mils in height.
   d. In the range between 750 mils and 1000 mils in height.

CALIBRATION PROCEDURE FOR OUTSIDE MICROMETER

Introduction and Description

This procedure is to be used for an outside micrometer. It is specifically outlined for a one-inch micrometer, however, it may be used for any outside micrometer using these same basic principles.

Check the particular micrometer size and range which needs to be calibrated. The outside micrometer caliper is defined in terms of the maximum measurement obtained by the instrument.

Equipment Requirements

A set of gage blocks will be necessary for the micrometer calibration procedure. These are used for checking the instrument over each quarter of its total measurement span. For example, a one-inch micrometer may be calibrated using four gage blocks of the following sizes:

1. Less than 250 mils.
2. In the range between 250 and 500 mils.
3. In the range between 500 and 750 mils.
4. In the range between 750 and 1000 mils.

Preliminary Operations

Perform a visual inspection of the micrometer ensuring:

1. Cleanliness of the measuring faces.
2. Proper operation of the barrel and thimble.
3. Proper operation of the friction or adjusting nut used to compensate for wear between the screw portion of the spindle and the nut.
4. For micrometers furnished with a spindle lock or clamp ring, the use of this device shall not alter the distance between measuring faces by more than 0.0001 inch.

5. Micrometers are usually designed for operation at approximately 68°F. Verify this for the micrometer in question and ensure that room temperature is 68° ± 2°F.

Calibration Process

1. Set the micrometer faces to the "closed" position and "zero" check the micrometer. Repeat this operation 5 times taking the average of all five readings.
2. Open the micrometer faces and insert the gage block that is less than 250 mils in level and measure this calibrated block 5 separate times, taking the average of all five readings.
3. Repeat step 2 for each of the three remaining gage blocks taking five separate measurements for each block and once again averaging the readings.
4. From the average of each of these five measured readings at each of the five measured locations, determine if the micrometer is accurate to within ± 0.0005 in. of the gage block reading. (Note; the accuracy of a specific micrometer may be greater than ±0.0005 in. In these cases, the micrometer should be calibrated taking the actual designated accuracy into account).

DATA TABLE

None.

REFERENCE MATERIALS

IEEE Std 498, Requirements for the Calibration and Control of Measuring and Test Equipment Used in the Construction and Maintenance of Nuclear Power Generating Stations, The Institute of Electrical and Electronic Engineers, 345 East 47th Street, New York, New York 10017

Busch, Ted, Fundamentals of Dimensional Metrology, Delmar Publishers, Third Edition, 1966.

Covino, Charles P. and Meghri, Angelo W., Quality Assurance Manual, The Industrial Press, First Edition, New York, New York, 1962.

Farago, Francis T., PhD., Handbook of Dimensional Measurement, Industrial Press Incorporated, Third Printing, 1968.

Juran, J.M., Quality Control Handbook, McGraw-Hill Book Company, New York, New York, Third Edition, 1974.

Society of Manufacturing Engineers, (SME), Handbook of Industrial Metrology, Prentice-Hall, Incorporated, 1967.

National Conference of Standards Laboratories

- Recommended Practice #1, Establishment and Adjustment of Calibration Intervals
- Recommended Practice #3, Preparation of Calibration Procedures
- Recommended Practice #4, Calibration System Specifications

TEST

Read each question carefully. Be sure to provide the specific information each question requires. Make your answers brief. Use the backs of the test if you need more space.

1. Define the following terms:
   a. calibration
   b. traceability
   c. national standard
   d. reference standard
   e. out-of-calibration

2. Describe the role of the U.S. National Bureau of Standards with respect to calibration.

3. State the principle associated with traceability and describe its role in the calibration program.

   a. principle____

   b. role____

4. Name four sources which may independently cause an instrument to be out-of-calibration.

   a.____

   b.____

   c.____

   d.____

5. Briefly describe the contribution to calibration program by each of the following elements of a calibration program:

   a. calibration procedures____________________________

   b. intervals of calibration__________________________

c. recall procedure

d. precalibration checks

e. labeling

Multiple Choice. For question 6 through 11, circle the letter of the choice which best answers the question or satisfies the statement.

6. The most prevalent method of adjusting calibration intervals is by "educated guess" by experienced persons. This method is called:
   a. fixed interval through data
   b. fixed interval through engineering judgement
   c. variable interval
   d. use time interval

7. What is the name of the method of adjusting intervals of calibration wherein each individual instrument's calibration interval is adjusted at each calibration?
   a. fixed interval through data
   b. interval by use time
   c. interval by in use testing
   d. variable or floating interval

8. The method of adjusting intervals of calibration by fixed interval through data method relies upon:
   a. judgement of experienced persons
   b. statistical analysis of calibration results for each grouping of instruments
   c. collection of "on" time as indicated by usage tags
   d. frequent checks of critical parameters during normal use of the instrument.

9. The limits of accuracy to be met by instruments at calibration is specified by each company based upon:
   a. national standards
   b. calibration history data of instruments
   c. capability and expected use of instruments
   d. known intervals of calibration.

10. Whenever an instrument is found to have evidence of damage, it is identified as:
   a. calibrated
   b. calibration not required
   c. removed from inventory
   d. nonconforming.

11. A definite relationship between the accuracy of an instrument and the national standard is provided by:
   a. labeling
   b. recall procedures
   c. tolerance-to-accuracy principle
   d. traceability.

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Matching. Match the record with its primary purpose by placing the proper letter from the right hand column adjacent the purpose in the left hand column:

Purpose

____ 12. provides historical evidence of calibration results

____ 13. serves as an accountability record for individual instruments

____ 14. provides an inventory of instruments.

Record

a. master serialization listing
b. instrument assignment log
c. calibration record card
d. delinquent report
e. status label

Match the environmental condition with its adverse effect on calibration by placing the proper letter from the right hand column adjacent the adverse effect in the left hand column:

Adverse effect

____ 15. interferes with wringing of gage blocks

____ 16. too little causes static electricity

____ 17. may affect operation of electronic comparator amplifiers

____ 18. affects accuracy of measurement with test indicator used with height stand and long fixturing

Environmental condition

a. temperature
b. humidity
c. vibration
d. electromagnetic interference
e. dust
f. fumes

Read the following descriptions of calibration events and state the single most important omission by the calibration technician.

19. A sixteen inch outside micrometer is taken to the laboratory for calibration. The technician immediately calibrates the micrometer using calibrated length rods

and gage blocks. The micrometer is accurate throughout its range within specified limits, no adjustments are made, a new label is applied, and the calibration record card is completed.

____

____

20. A depth micrometer assigned to the calibration laboratory is due for calibration. The technician disassembles the micrometer, cleans the lubricates it and reassembles it. Using surface plate, squares and gage blocks, the technician adjusts the micrometer to be accurate within specified limits. A new label is applied and the calibration record card is completed.

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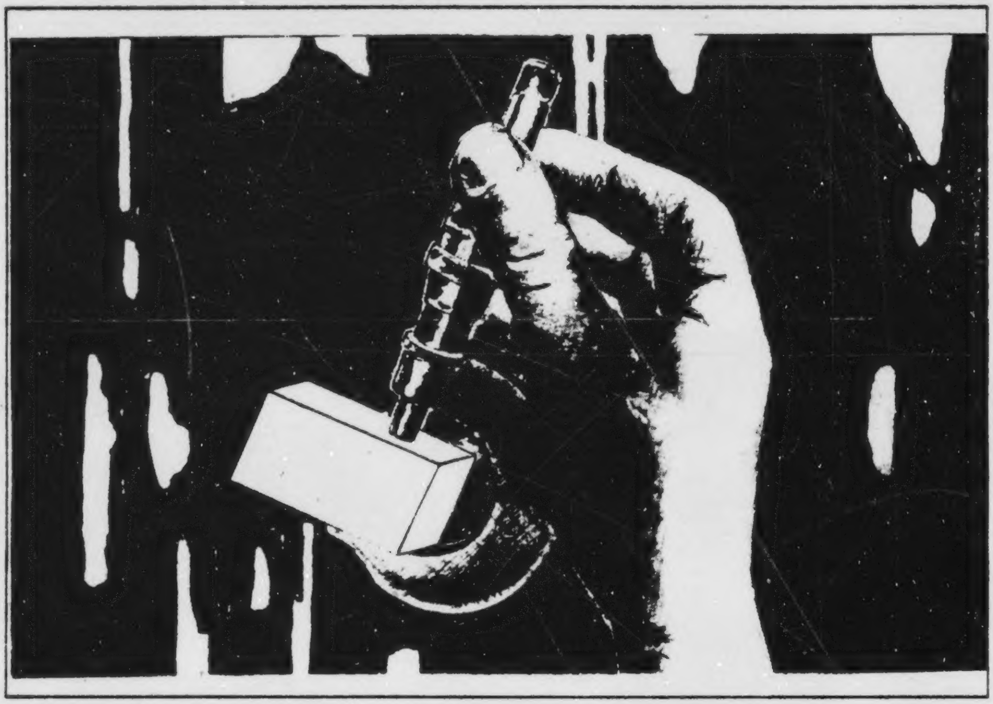
NUCLEAR TECHNOLOGY

MODULE 27 - 7

STATISTICAL TECHNIQUES IN METROLOGY



COURSE 27: METROLOGY

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COURSE 27 METROLOGY

MODULE 27-1	Fundamentals of Metrology
MODULE 27-2	Fixed Gages, Dividers, Calipers and Micrometers
MODULE 27-3	Gage Blocks, Mechanical Comparators and Electronic Comparators
MODULE 27-4	Angle Measurement Instruments, Optical Projectors and Surface Texture Gages
MODULE 27-5	Tolerancing
MODULE 27-6	Calibration
⇨ MODULE 27-7	Statistical Techniques in Metrology
MODULE 27-8	The Total Measurement System

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INTRODUCTION

The QA/QC Technician's responsibilities include the determination of acceptability or non-acceptability of all parts received at a nuclear plant or construction site. In addition to verifying that shipping, packaging and storage requirements have been met for these parts, the QA/QC Technician must determine the likelihood that parts received are going to function in a satisfactory way when put into use in the various operating systems for which they are intended. Another such responsibility is the determination that the various systems, such as a pumping system, are likely to be functioning properly. It must be known, among other things, whether or not the "dimensions" and "tolerances" are within prescribed limits for each type of part received. It must be known if a pumping system is pumping liquids at the prescribed temperature and pressures.

Given the number of parts that can be received in a single shipment (in the thousands) or the volume of output of a pumping system (in the thousands of gallons), it is unreasonable to expect an examination of every part received. It is unreasonable to expect continuous measurement of a system's output. Therefore, the QA/QC Technician needs to know how to make decisions about the acceptability of a total shipment of parts by examining some representative sample of these parts. She/he must make a decision about a system's output from a sample of measurements of the system's output. To accomplish these tasks, it is essential to recognize and apply basic statistical concepts that relate data gathered from a sample of objects to predictions about the entire set of objectives.

It is extremely important that such samples of objects be *random samples*. A sample is said to be random when every object in the entire set of objects has the same chance of being selected for the sample as every other object in the entire set. If the sample is not random, then any prediction based on the sample is likely to be in error. The sample is then said to be *biased*. In the mid 1930's, a poll was taken of a sample of voters to predict the winner of the 1936 presidential election. The results of the poll indicated that Alf Landon would win by a landslide. Of course, history records Franklin D. Roosevelt as the overwhelming choice of the public. The problem with the prediction was a biased sample. Names were chosen at random from telephone directories and state motor vehicle records. However, telephones in the 1930's were most likely to be possessed by upper middle class and upper class whites, and automobiles were owned predominantely by older, white, upper-middle class and upper class males. These people were most likely to be republican. Middle and lower class, white collar and blue collar workers who were likely to be democrats did not have the same chance to be selected for the sample as did the upper-middle class white male republicans. The sampling plans presented in this module employ procedures for selecting truly random samples so as not to be subject to errors introduced by sampling bias.

Statistical techniques are employed in metrology in three important ways:

1. descriptive statistics, such as the average size or weight of an item, are used to define the characteristics;
2. inferential statistics are used as a basis for sampling some items from a batch of manufactured goods and deciding if the entire batch should be accepted or rejected;
3. assessing the accuracy of the measuring instrument itself.

This module will concentrate upon the first two uses, but it should be noted that the way a person measures an object always affects the accuracy of the results. It is not unusual for two people to come up with slightly different numbers when measuring the same object. Statistical techniques covered in points 1 and 2 above will provide the QA/QC technician with a method for quantifying the measurement variations that result from the equipment used as well as from the person making the measurements.

Often the patterns of variation look very much like the *Gaussian distribution curve,* commonly called the *"normal curve"*, which is probably the most utilized tool for anyone making a statistical analysis. It has been used, with varying degrees of justification, to describe the distribution of the heights of males and of females, the sizes of beans, the weights of newborn babies, the velocities of particles in a gas, the number of chocolate chips in cookies, and numerous other properties of the physical and biological worlds. The normal curve will figure quite prominently in some of the quality control work presented in this module.

MODULE PREREQUISITES

A Basic Algebra Course is essential for this module. The student/trainee shall also have completed all previous modules of this course.

OBJECTIVES

Upon completion of this module, the student/trainee can do the following:

1. Describe the general responsibilities of the QA/QC technician with respect to quality assurance, quality control and process control at a nuclear plant or construction site.
2. Given a set of measurements, identify the appropriate *measurement cells* and their corresponding mid-points or mid-values.
3. Given a set of measurements construct a *frequency distribution* (tally sheet) of the measurements using appropriate measurement cells.
4. Given a set of numbers, compute the *mean* and the *standard deviation* using the formulas:

   $$\text{Standard deviation} = s = \sqrt{\frac{N\Sigma fx^2 - (\Sigma fx)^2}{N(N-1)}}$$

   $$\text{Mean} = \bar{x} = \frac{\Sigma x}{N}$$

5. Describe three quality acceptance *sampling* schemes and state the weaknesses and strengths of each scheme.
6. Describe the risks associated with sampling procedures.
7. Given a set of sampling parameters and MIL-STD-105D, identify the appropriate sampling size and the acceptance and rejection *criteria*.

NOTES TO INSTRUCTOR / STUDENT

Some of the formulas and procedures presented in this module were chosen to facilitate the use of pocket calculators -- in particular the formula for the *standard deviation** of grouped data. It is recommended that the student/trainee be given instructions if necessary and the opportunity to practice the use of the pocket calculator. If you (the instructor) prefer a more sophisticated treatment of the standard deviation, then any suitable statistics text may be used as a supplement.

An appropriate lab exercise that you might use to summarize and review the content of the module if it is possible at your location is as follows: Provide the student/trainee with a single box of nails which might represent a shipment received. Have each student/trainee select a sampling plan and make the appropriate measurements on the sample with a micrometer. The student/trainee will then perform all appropriate calculations, and with the use of MIL-STD-105D, accept or reject the lot. The measurement data obtained by each student/trainee could then be polled and the precision of the measurements could be determined.

*NOTE: All italicized words in this module are defined in in the glossary of terms.

SUBJECT MATTER

GLOSSARY

- AQL - Acceptable Quality Level (associated with Producer's Risk).
- Acceptance inspection - a process for estimating the qualities of a group of items called a "lot" and then deciding to accept or reject the lot.
- Acceptance number - cut-off level set by sampling plan that specifies the maximum number of defectives that can be found and still have the lot accepted.
- Attribute data - refer to measurements collected with regard to whether they are within or beyond same specified requirement.
- Biased sample - a group of measurements that are not randomly drawn from the population.
- Consumer's risk - probability that a bad lot will yield an acceptable sample.
- Cell limits (boundaries) - are the extreme upper and lower measurements allowable in a measurement cell.
- Central tendency - most commonly refers to the arithmetic mean that is found by summing the sample measurements and dividing by the number of measurements taken.
- Criteria - a standard agreed upon for statistical evaluation purposes.
- Deviation - dispersion of measurements about a central tendency.
- Frequency - is the number of times (f) that a particular measurement (x) occurs in a measurement cell.
- Frequency distribution - a graph of the number of measurements observed within each of the measurement cells.

- Gaussian (normal) curve - a frequency distribution (e.g., of sample measurements) that looks like a "bell" shape.
- Interval - units of measurements on a scale.
- Interval of uncertainty - the unit on a scale that spans the mid-point of a measurement cell and within which, measurements are considered equal to each other.
- Lot - collection of discrete units.
- LTPD - Lot Tolerance Percent Defective (associated with Consumer's risk) - level of defectiveness that is unsatisfactory and thus should be rejected by the sampling plan.
- Mean - is the average of a set of measurements found by summing the measurements and dividing by the number of measurements.
- Measurement cell - represents an interval of uncertainty concerning true measurements.
- Mid-point (mid-value) - of a cell is the value obtained by adding the cell limits and dividing by 2.
- MIL-STD-105D - Military Standard (see resource list at end of module).
- Normal curve - see Gaussian distribution curve.
- Operating - characteristic curve (OC curve) - graphically represents the tradeoff between the chance of acceptance of a lot and the quality of the lot. (See Figure 27-7-8).
- P_a - probability of lot acceptance.
- P_r - probability of lot rejection.
- Probability - likelihood of an event taking place (usually expressed as a ratio).
- Process control - involves the taking of successive samples of output of a system and applying statistical

techniques to determine if the system output is under control.

- Producer's risk - probability that a bad lot will yield an acceptable sample.
- Random samples - a group of measurements made on items (events) drawn from a population (lot) in a non-biased or equal-probability fashion.
- Range - the measure of variability that is obtained by taking the largest measurement minus the smallest measurements, the difference being the range.
- Sampling plan - a method for taking measurements on a sample drawn from a lot (or process) and the statistical treatment of the measurements in order to accept or reject the lot (or process control).
- Standard deviation - a measure of dispersion of a set of numbers about the mean (see formula in Central Tendency section).
- Summation - symbolized by a greek sigma (Σ), denotes a list of measurements (x's) to be added together.
- Variable data - measurement data that represent specific or exact values.

DATA COLLECTION

Collecting data can be considered detective work -- "numerical detective work" -- or "graphical detective work". In the case of the QA/QC person, clues are being sought as to the character of shipments received. She/he is looking for information concerning the reliability or usability of parts. The QA/QC person, however, is more than a detective. She/he is also judge and jury. She/he collects data, organizes and evaluates data, and determines the fate of the shipment (accept or reject).

The first task after measurements are taken and collected is to write down the numbers in such a way that a general idea of "what they are like" is presented. Some examples of such groups of measurements are (a) the average speed of each car in a particular race, (b) the batting averages of baseball players on a certain team, (c) the number of ads for QA/QC Technicians in all of the newspapers in each of ten major cities in the United States, or (d) the heights of fifteen 10th graders in a particular homeroom. There are many ways to write down these sets or groups of numbers.

The heights of the 10th graders, for example, may be written as they were taken: 5' 9.5", 5' 6", 5' 11.5", 6' 3", 5' 11", 5' 9.5", 5' 11", 5' 6", 5' 6.5", 5' 11", 5' 11", 6' 2", 5' 9", 5' 8.5", 5' 11.5".

This arrangement does give some idea of what the heights of the 10th graders are like but there are ways to write these numbers to get a clearer picture. For example, they may be written in order from shortest to tallest: 5' 6", 5' 6", 5' 6.5", 5' 8.5", 5' 9", 5' 9.5", 5' 9.5", 5' 11", 5' 11", 5' 11", 5' 11", 5' 11.5", 5' 11.5", 6' 2", 6' 3".

With this arrangement, it can be seen at a glance that the heights of the 10th graders range from 5' 6" to 6' 3". It is a better picture of "what they are like" than is the random picture first presented above; however, another picture may be presented by using a chart that shows the frequency of each of the heights as shown in Figure 27-7-1.

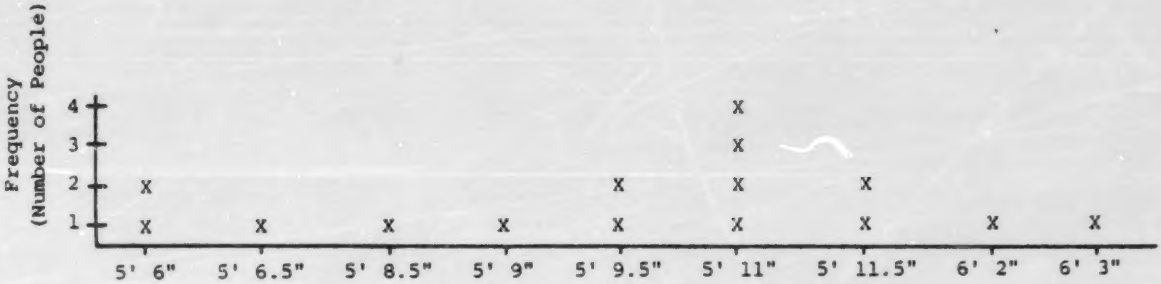


Figure 27-7-1 Frequency Distribution According to Height

With this arrangement it can easily be seen that the *range* of heights is from 5' 6" to 6' 3", and in addition it can easily be seen that four 10th graders are 5' 11", two are 5' 11.5", two are 5'6". What is not readily obvious from this arrangement, however, is that no 10th grader is 5' 7" or 5' 8" or 5' 10" etc. If a chart were used that showed all possible heights in half inches from 5'6" to 6'3", this information would be readily available by simple inspection:

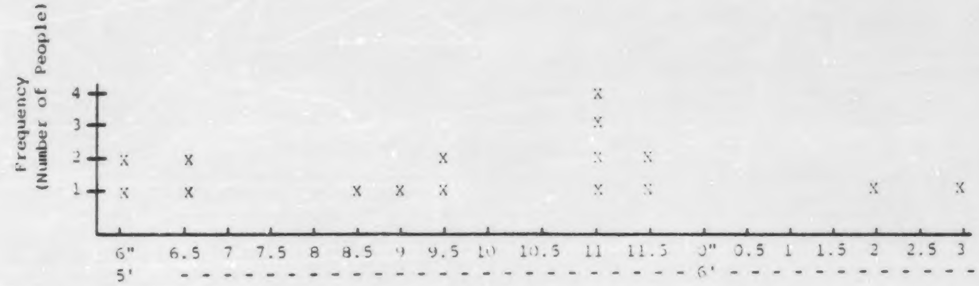


Figure 27-7-2 Frequency Distribution According to Height Shown in Half -inch Increments.

Measurement Cells

It should be noted that no measurement is absolute but only an approximation. In the examples above, it would be accurate to have described the measurements as approximately 5' 11" or approximately 6' 2" etc. How approximate depends on the measuring device that is used. (See Module 24-4). For any measurement that is made, other than a frequency count, there is always an *interval of uncertainty*. This interval depends upon the scale used on the readout device. For example, if the measuring instrument is centimeters (see Figure 27-7-3), the measures of each of the segments $\overline{AB}$, $\overline{CD}$ $\overline{EF}$, and $\overline{GH}$ would be reported as 3 centimeters to the nearest centimeter. The line segment, $\overline{MN}$ and $\overline{OP}$ would be reported as 8 centimeters to the nearest centimeter. For $\overline{AB}$, $\overline{CD}$, $\overline{EF}$, or $\overline{GH}$ all we can be sure of is that the true measure is between 2.5 and 3.5. This is an interval of uncertainty. For $\overline{MN}$ and $\overline{OP}$ this interval of uncertainty is from 7.5 to 8.5. It is possible to make use of these intervals of uncertainty and construct something called measurement cells.

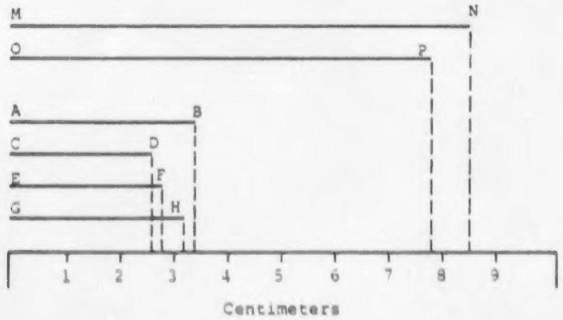


Figure 27-7-3 Measurement Cells Denoting an Interval of Uncertainty

Taking the average of the measures that group together and halving the interval of uncertainty yields a statistical tool called a measurement cell.

Measurement cell = average value ± ½ (interval of uncertainty)

In Figure 27-7-3 we would then have two measurement cells at 3 ± 0.5 and 8 ± 0.5.

In Figure 27-7-4, the interval of uncertainty is stated as ±0.5 about each average measurement in centimeters and inches.

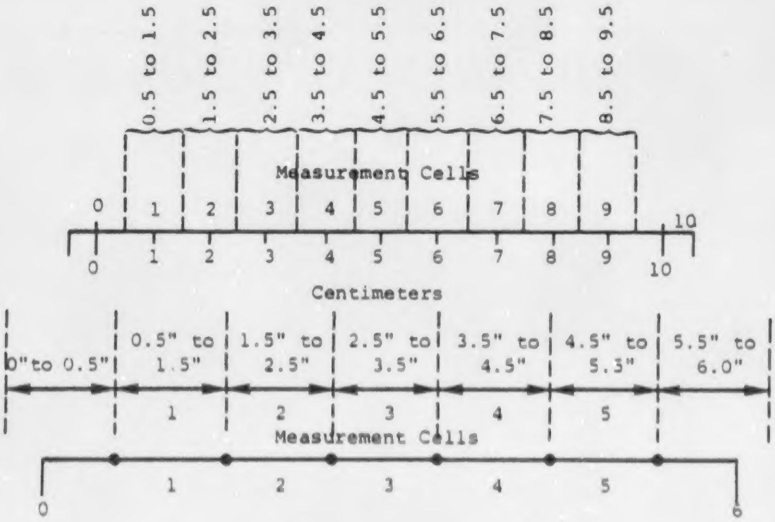

0.5 to 1.5
1.5 to 2.5
2.5 to 3.5
3.5 to 4.5
4.5 to 5.5
5.5 to 6.5
6.5 to 7.5
7.5 to 8.5
8.5 to 9.5
Measurement Cells
0 1 2 3 4 5 6 7 8 9 10
0 1 2 3 4 5 6 7 8 9 10
Centimeters
0" to 0.5"
0.5" to 1.5"
1.5" to 2.5"
2.5" to 3.5"
3.5" to 4.5"
4.5" to 5.3"
5.5" to 6.0"
1 2 3 4 5
Measurement Cells
1 2 3 4 5
0
6

Figure 27-7-4 Measurement Cell Example

Even though no measurements are absolute, they can be treated as absolute in terms of the measurement cell to which they belong. The value assigned is the value of the midpoint of the interval to which its measurement belongs. In Figure 27-7-3, the value assigned to $\overline{AB}$, $\overline{CD}$, $\overline{EF}$, and $\overline{GH}$ is 3. 3 is the midpoint of the cell to which all of these measurements belong.

In general, the *midpoint* or *midvalue* of a cell is the value assigned to all measurments that fall within the cell limits or boundaries. *Cell limits* or *boundaries* are the extremes within which measurements must lie if they are to be assigned the value of the midpoint. In Figure 27-3-3, these cell limits or boundaries for the measures assigned $\overline{MN}$ and $\overline{PO}$ are 7.5 and 8.5.

For tolerance measurements, if parts are being measured to the nearest 0.001 inch and they run approximately 0.1000 inch, the cell for this value would be 0.1000 as the midpoint and 0.0995 as the lower cell limit and 0.1005 as the upper cell limit, or 0.1000 ± 0.0005. This could be shown as follows:

Cell Midpoint	Cell Limits
0.1000	0.1005
	0.0995

Note that this means that any reading greater than 0.0995 and less than 0.1005 would be considered 0.1000. Assuming a cell interval of 0.001 and an average size of 0.103, the following would be a way to tabulate the data collection:

Table 27-7-1

Cell Midpoints and Cell Limits Table

Cell Midpoints	Cell Limits
	0.1075
0.107	
	0.1065
0.106	
	0.1055
0.105	
	0.1045
0.104	
	0.1035
0.103	
	0.1025
0.102	
	0.1015
0.101	
	0.1005
0.100	
	0.0995
0.099	
	0.0985

Cells could be added or deleted from each end as needed.

Once the measurement cells have been established, data can be collected by tallying (or counting up) the measurements that fall in their appropriate cells, using the midpoint as the value.

NOTE: Cell intervals need not be in units of one. However, once established, a cell interval must be constant for a given distribution (tally).

CENTRAL TENDENCY

The writing down of sets of numbers to get a good idea of what "they are like" is very useful to the numerical detective, but there are characteristics of these sets that are not apparent for any display of the numbers themselves. Of interest to the statistician, among other things, concerning groups of measurements are the *central tendencies* of these numbers. Central tendencies are determined by arithmetic computation quite often. One such measure of a central tendency is the arithmetic *mean* (denoted by $\bar{x}$), which is computed by summing all of the measurements in the group and dividing that sum by the number of measurements in the group. For example, consider the following group of 7 numbers: 15, 19, 23, 12, 27, 35, 16.

The formula for the mean is:

$$\bar{x} = \frac{\sum_{i=1}^{k} X_i}{N}$$

In the formula above, $\bar{x}$ = the mean or average of the measurements x, Σ = summation of all x values, from subscript i = 1 to i = k (all x values here), N = number of measurements summed.

The calculation proceeds as follows:

$$\bar{x} = \text{The mean} = \frac{15 + 19 + 23 + 12 + 27 + 35 + 16}{7}$$

$$\bar{x} = \frac{147}{7}$$

$$\bar{x} = 21$$

The measures of certral tendency, such as the mean, do provide more information about what the measures look like, than just the displays of numbers; however the mean does not tell very much about how the measures disperse themselves around the mean.

In the following example, Figure 27-5-5, 18 people's scores on a test have a mean of 50.

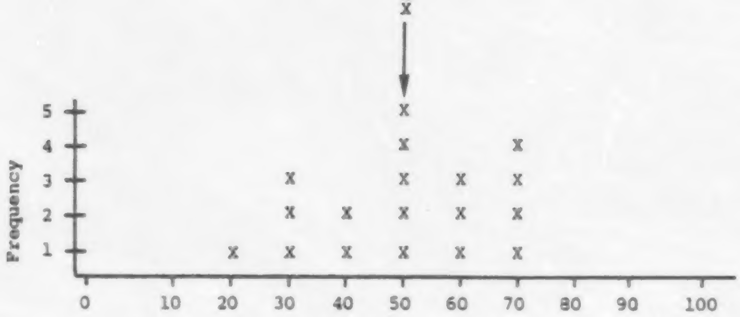


Figure 27-7-5 Frequency vs. Score Graph Displaying Central Tendency

The scores range from 20 to 70. They cluster around 50 (the mean).

Another group of 18 scores for the same test might also have a mean of 50 with a wider spread (dispersion) of scores. See Figure 27-7-6.

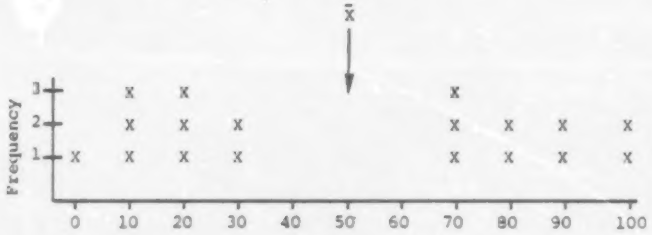


Figure 27-7-6 Frequency vs. Score Graph Showing Wider Dispersion of Data

These 18 scores range from 0 to 100. They do not cluster near their mean of 50, but are more widely spread out from the mean.

In the example shown in Figure 27-7-5, the measures *deviate* very little from the mean while in the example in Figure 27-7-6, the measures deviate quite a bit from the mean. These deviations give the numerical detective (the QA/QC person) more information and therefore, an even better picture of what the measures are like than does a tally sheet.

They give a picture of how the individual measures are dispersed about the mean of the measures.

The Standard Deviation

The most widely used measure of the dispersion, or scatter, of scores about their mean is the *standard deviation*. As has been seen, the mean value of any set of measurements (for example, the lengths of a bolt) can always be computed. However, this gives no information about the likely uncertainty in subsequent measurements. Knowledge of the standard deviation for a set of measurements allows us to make a statement such as "it is 50% probable that a future measurement of the bolt length will lie between some upper limit (say 6.2 inches) and some lower limit (say 6.0 inches). These limits are established by the value of the standard deviation, with a larger value signifying a large uncertainty and vice versa.

The formula for the *standard deviation* is:

$$s = \sqrt{\frac{N\Sigma fx^2 - (\Sigma fx)^2}{N(N-1)}}$$

Where

s = standard deviation
$\sqrt{}$ = square root
N = number of all measurements taken
Σ = the sum of
f = frequency of scores in measurement cell
x = midvalue of measurement cell

The formula will provide a measure of dispersion that is not available from calculating the mean alone.

An illustration of the use of a data table to determine the standard deviation of a set of measurements is presented below:

Measurement Cell	Mid-Point (x)	Frequency (f)	$f \cdot x$	x^2	$f \cdot x^2$
14-16	15	1	15	225	225
12-14	13	2	26	169	338
10-12	11	4	44	121	484
8-10	9	3	27	81	243
6-8	7	1	7	49	49
Sums		N = 11	$\Sigma fx = 119$		$\Sigma fx^2 = 1339$

The standard deviation, s, is:

$$s = \sqrt{\frac{N\Sigma fx^2 - (\Sigma fx)^2}{N(N-1)}}$$

$$s = \sqrt{\frac{11(1339) - (119)^2}{11(10)}}$$

$$s = \sqrt{\frac{14729 - 14161}{110}}$$

$$s = \sqrt{\frac{568}{110}}$$

$$s = \sqrt{5.164}$$

$$s = 2.272$$

The mean value, $\bar{x}$, is:

$$\bar{x} = \frac{\Sigma f \cdot x}{N}$$

$$\bar{x} = \frac{15 + 26 + 44 + 27 + 7}{11}$$

$$\bar{x} = 10.818$$

THE NORMAL CURVE

The *standard deviation* is most frequently used in connection with something called the *normal curve*. It was stated in the introduction to this module that the patterns of variations in every aspect of measurement often look like a normal curve. This is particulary true when the measurements represent a large number of objects or outcomes. In these instances, most of the measurements tend to cluster near the mean with fewer measurements found at the extremes. To illustrate this, consider the distribution of scores represented in Figure 27-7-5 and figure 27-7-6. If the columns of x's are united by a curve as in Figures 27-7-7a and b, the curves that are formed are difficult to describe.

In the first case, the measurements are all close to the mean with none at either extreme. In the second case, all measurements are at one extreme or the other with none near the mean. When most of the measurements are near the mean with a few at both extremes the curve takes on the appearance of a bell. Please refer to Figure 27-7-8a and b. When this happens, the curve that is formed is called a normal curve and the measurements are said to be normally distributed or dispersed about the mean.

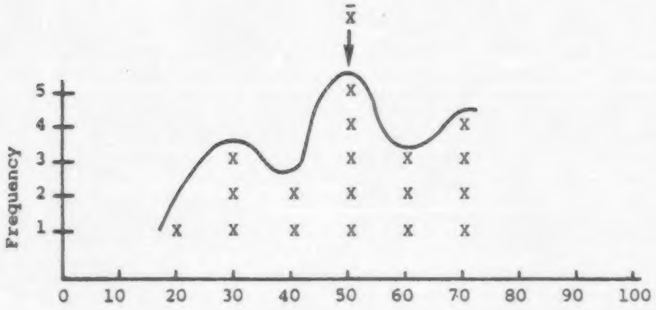


Figure 27-7-7a Frequency vs. Score Graph Showing Central Tendency

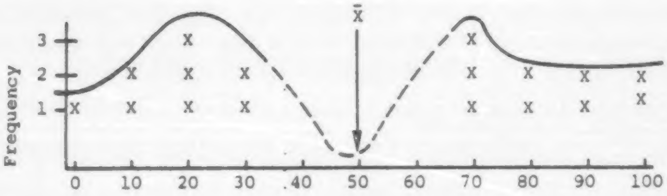


Figure 27-7-7b Frequency vs. Score Graph Showing Wider Dispersion of Data

Area Under the Curve

In normal distribution of measurements, the standard deviation of the measurements is used to determine the area under the normal curve. The standard deviation is commonly used as the measurement unit. The total area under the curve is said to be 100%.

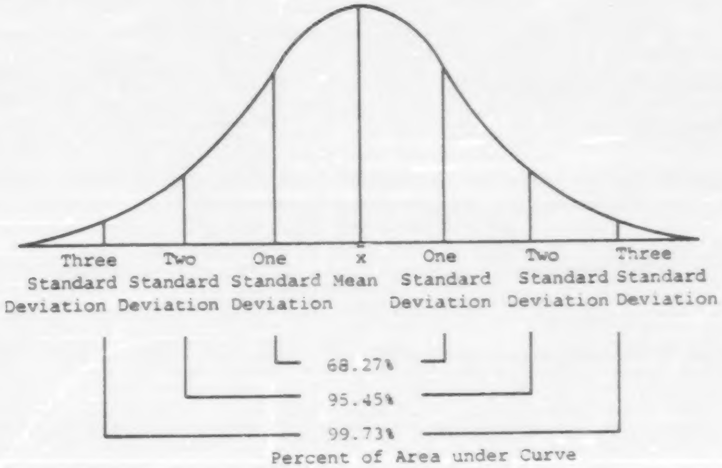


Figure 27-7-8a Theoretical Normal Distribution

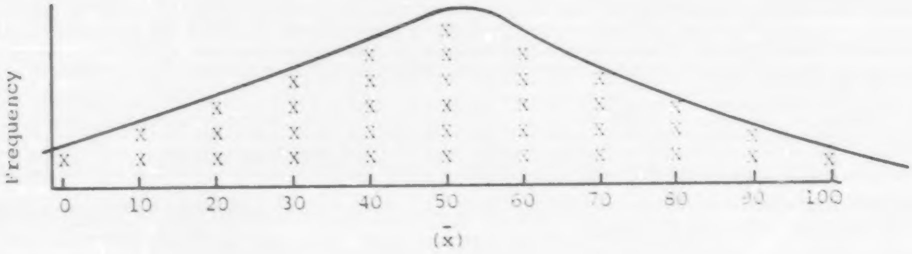


Figure 27-7-8b Observed Normal Distribution

In a normal distribution, 34.135% of all measurements are within an interval of one standard deviation above the mean; another 34.135% are within an interval of one standard deviation below the mean. This means that 68.27% (34.135% + 34.135%) of measurements are found in a central interval from one standard deviations below the mean to two standard deviation above the mean. 95.45% are in an interval from two standard deviation below the mean to two standard deviations above, and 99.73% will be in an interval from three standard deviations below to three standard deviations above. See Figure 27-7-8a.

Uses of the Normal Curve

The QA/QC Technician can use the properties of the normal curve in making decisions in both acceptance inspection and process control operations. For example, if a supplier of screws claims that the mean of the measurements of the screws' lengths are 2.5 cm. with a standard deviation of ± 0.05 cm., the QA/QC Technician can use this information to determine the expected range of measurements of the lengths of the screws in the shipment. Thinking in terms of the normal curve (See Figure 27-7-9) the technician knows:

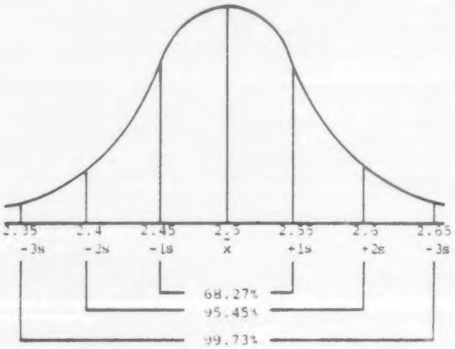


Figure 27-7-9 Expected Normal Distribution for Screw Measurements.

1. 68.27% of the screws should measure between 2.45 cm. and 2.55 cm. - the limits of the central interval (±1 standard deviation).
2. 95.45% of the screws should measure between 2.4 cm. and 2.6 cm. (±2 standard deviation).
3. 99.73% of the screws should measure between 2.35 cm. and 2.65 cm. (±3 standard deviations).
4. Only 3 screws in every 1000 should be either longer than 2.65 or shorter than 2.35 cm.

Now when the QC/QA Technician measures the lengths of a representative sample of screws from the shipment, he/she knows what measurements to expect if the mean is really 2.5 cm. (that is if all screws could be measured) with a standard deviation of 0.05 cm. If the measurements of the sample are "too much" different from what is expected, the technician has strong evidence to suspect that the supplier's claims about the mean and/or standard deviation of this shipment of screws is not valid. This kind of information is valuable in deciding whether to accept or reject the shipment.

The Exercise and Procedures sections of this module give problems with solutions which reinforce the concept of THE NORMAL CURVE. These should be worked to ensure proper understanding of this material.

TYPES OF DATA

There are basically two types of measurement data - variable and attribute - that the QA/QC people must deal with. *Variable data* are measurement data that represent specific values. The examples given previously in the section on DATA COLLECTION cited that a) the average speeds of each car in a specific race, b) the batting averages of baseball players on a certain team, c) the number of ads for QA/QC positions in newspapers and d) the height of fifteen 10th graders, are all examples of variable data. *Attribute data* are data that indicate whether measurements are within or beyond some specified requirement. For example, a sample of bearings are being examined by a type of tolerance gauge where those that do not pass through are rejected. Specific measurements of each bearings are not made, only a measurement of whether or not each bearing is within or beyond some specific requirement. It should be noted that whether data is variable or attribute really depends on how the data is used. Specific measurements may be taken but the data could still be attribute. For example, the Military Academy at West Point will not accept applicants who are over 6'6" tall. Specific measurements of heights are made but they are classified as under 6'6" or over 6'6". They are either within or beyond a specified requirement. They are attribute data.

In many instances at receipt inspections, the QA/QC Technician may find it impractical or not necessary to secure specific measurement data. It may be desirable to consolidate a number of quality characteristics such as those of an assembly and simply define the entire unit as conforming or non-conforming. These kinds of data are normally expressed as either percent defective or rejected of the pieces inspected and/or tested. However, on occasion, the QA/QC will deal with the variable data, particularly with respect to something called *process control*. This will be discussed more fully later in this module.

STATISTICS AND REPETITIVE PROCESSES

All of the previous ideas come together in systematic statistical quality control, which is the statistical surveillance of repetitive processes. Any repetitive process may call for quality control. For example, turning out rivets, building coolant pumps, generating electricity, receiving purchase orders, or recycling water involve a large volume of activity composed of distinct units repeated many times. The purposes of statistical quality control are (1) ACCEPTANCE INSPECTION, which tries to evaluate past performance, and (2) PROCESS CONTROL, which attempts to estimate present and future performance. In both cases decisions are made on the basis of samples taken. On the basis of an analysis of the sample, in process control it might be decided whether a process is still under control while for acceptance inspection an estimate of the qualities of a group of items, called a "lot", is made and the lot is accepted or rejected. Most of the QA/QC person's time in statistical surveillance of repetitive processes will be spent in acceptance inspection at the times of receipt inspections. However, he/she will have occasion to become involved in process control and therefore both concepts are presented in this module.

ACCEPTANCE INSPECTION

The QA/QC person might receive a shipment of detonating fuses and have the responsibility for designating the entire lot as "acceptance" or "unacceptance". Assuming that the installation can tolerate no more than 2% of those fuses as duds, how can it be fairly ascertained that the entire shipment meets those specifications? Obviously, all of the fuses cannot be tested no matter how large or small the shipment size, as testing destroys them. Therefore, only a sample is tested. If the sample contains a specified number of defective fuses or more, the entire lot is rejected -- otherwise it is accepted.

Even if testing did not destroy the items being inspected, it may not be desirable to test 100% of them. Inspector fatique, among other things would interfere with the accuracy of the results. According to Juran (Quality Control Handbook, p. 12-51) 100% inspection at best is only correct 80% of the time. Sampling procedures reduce the opportunity for inspection error in individual measurements.

Such a sampling plan has two risks: first, there is the risk that a good lot will yield a bad sample; and second, the risk that a bad lot will yield a good sample. Now the first risk is not really the problem of the buyer, as the good lot which tested bad would be taken back by the producer. The risk is generally termed the *producer's risk,* or the seller's risk.

The second risk is the problem of the buyer. A small sample could be tested, and just by the luck of the draw be a good sample which would lead to acceptance of the entire lot. This risk is termed the buyer's risk, or the *consumer's risk.* This risk should be kept as low as possible. One way to do so would be to check if the shipment included a certified control chart covering this lot. If the control chart were available, the QA/QC inspection could be limited possibly to only an audit of the supplier's control charts.

The second way to reduce this risk would be to use a sampling plan which gives an advantage to the buyer. Certain plans are more likely to assist the inspector in rejecting most of the bad lots that may be submitted, but they may increase the number of good lots mistakenly considered bad. Of course price might increase considerably if too many lots are rejected so both the buyer and the seller have an interest in both types of risks.

A variety of sampling plans exist - separate, well-thought-out procedures with clear rules for choosing a sample of a certain size in a certain way, and rejecting the lot if the number of defective items exceeds a specified number. With any given one, the acceptance or rejection of a lot is a matter of chance since it depends on a random sample. However, the probability of acceptance depends on the true quality of the lot -- which leads to the common saying that "quality cannot be inspected into the product, it must be built in."

The tradeoff between the chance of acceptance of a lot and the quality of the lot can be represented by an *operating-characteristic curve*, usually called an *OC curve*. Most OC curves resemble the Figure 27-7-10. The QA/QC Technician would accept a smaller and smaller percentage of the lots as poorer and poorer quality is considered. Obviously if the lot has zero percent defects, it is certain to be accepted; hence the OC curve always starts from 100. On the other end, if the lot has 100 percent defectives, it would certainly be rejected and the OC curve is at zero for that level of quality. The curve represents what a particular sampling plan will accomplish, and therefore it is of vital concern to the technican who must carry out the sampling and decide on the acceptance of a particular lot.

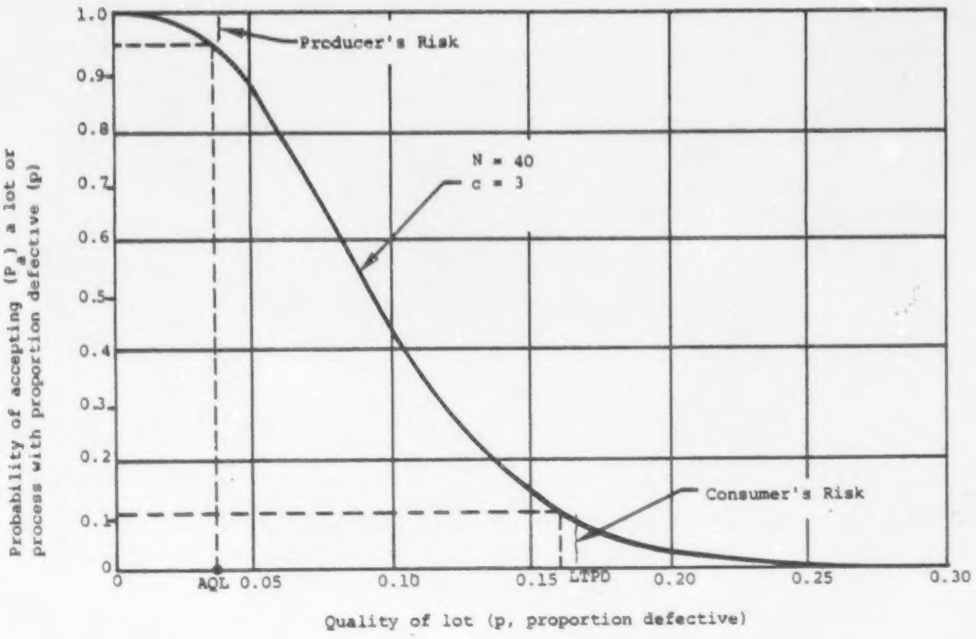


Figure 27-7-10 Operating-characteristic Curve for a Typical Sampling Plan Having a Sample Size = 40 and Acceptance Number = 3.

The points on the horizontal scale are possible lot quantities (i.e., proportions (P) defective), and the height of the curve shows the probability that a particular lot of this quality will be accepted (P_a) under a specified sampling plan. In the figure above, the sampling plan calls for accepting the lot if three or fewer defectives are found in a sample size of 40.

Thus if a lot that is 5 percent defective (0.05 on horizontal line above) is submitted to the plan whereby the sample size, N, is 40 and the acceptance number (c) is 3, there is slightly less than a 0.90 probability that the lot would be accepted. Note that one defective beyond the acceptance number calls for rejection of the lot.

Often the table is read in reverse fashion from the last interpretation. The *acceptable quality level* (AQL) is the level of quality at which the probability of acceptance of a lot is fairly large, typically around 0.95. For example in the illustration given, the AQL would be about 3 percent (0.03) if a 0.95 probability of acceptance were used.

Those same figures could be looked at another way. From the producer's point of view there is the risk that the material, whose quality is at the AQL, would be rejected by the acceptance plan. In the illustration, the producer stands a risk of 0.05 (1.00 - 0.95 probability of acceptance) that material that is 3 percent defective would be rejected.

At the other end of the curve is shown the consumer's risk, which is the risk that the user of the material takes that a lot of material actually having an undesirable quality level will be accepted by the plan. For example, in the figures above, the consumer is taking slightly over a 0.10 chance that material which is actually 15 percent (0.15 as as a proportion) defective will be accepted.

Sometimes the consumer risk is specified as a relatively low probability, generally 0.05 or 0.10. In the military standard entitled, "Sampling Procedures and Tables for Inspection by Attributes (MIL-STD-105D)," the term *Limiting Quality (LQ)* is used to refer to the lot quality associated with a particular consumer risk chosen. A second term related to LQ is the *Lot Tolerance Percent Defective (LTPD).* The LTPD refers to the lot quality associated with the specific probability of acceptance level of 0.10 (consumer risk of 0.10). In the example given in Figure 27-7-10 a LTPD of approximately 0.16 is observed (for a probability of acceptance (consumer risk) of 0.10.

Each sampling plan has a different OC curve, and the QA/QC Technician often uses different plans for different items being inspected. An ideal sampling plan would accept all good lots and reject all bad lots without error. But such a plan would require inspection of all, or practically all, of a lot. Assume for instance that two percent defectives or fewer is acceptable quality and over two percent unacceptable for a lot of 400,000 widgets. If one had taken a sample of 399,999 and found 8,000 defectives one would still not be absolutely certain that the lot was not over two percent defective -- the final item might be defective and 8,001 is more than two percent of 400,000. Therefore, unless some uncertainty in the immediate vicinity of the cutoff point is tolerated, complete inspection is necessary.

And even with 100 percent inspection there would not be certainty in practice of accepting all good lots and rejecting all bad lots. Even top-notch technicians and their instruments are fallible. A tendency exists to be less careful if a sample is large than if it is small. Worse yet, after a technician has looked at a few thousand items, they all begin to look alike. But the steepness of the OC curve depends on the sample size, and the steepness is the measure of the discrimination or sharpness of the test of acceptability. In many instances, the requirement for greater sharpness in differentiating between three and six percent defectives for given risks, for example, which might require a very large sample to be inspected, is balanced against the psychological advantage of a smaller sample with more careful attention by the technician. Of course 100 percent inspection makes little sense with destructive type testing such as explosive detonation, tensile, stress, rupture, or bursting type, as well as testing in which contamination of the material occurs with handling.

All sampling is based on randomness. For a truly random sample, all pieces within the lot must have an equal opportunity to be selected in the sample. Special care must be taken to insure randomness. Generally devices such as random number tables, dice, or playing cards are used to assure true randomness.

Four illustrative sampling inspection plans (see MIL-STD-105D) will show some of the variety encountered in practice. They are all based on an acceptable quality of 0.5 percent or fewer defective items in a lot.

- Single Sampling - Draw a random sample of 75 items and classify each one as defective or nondefective. With one or fewer defective, accept the lot; with two or more defective reject the lot.
- Double Sampling - Draw a random sample of 50, and classify them. Accept the lot if none is defective, reject the lot if three or more are defective. Otherwise (either one or two defectives) draw a second random sample, this time of 100 items. Now accept the lot if both samples together (150 items) contain two or fewer defectives, and reject it if the two contain three or more defectives.
- Multiple Sampling - In this type, double sampling is repeated a great many times until a final decision can be reached. As each additional random sample is taken, the combined number of defectives up to that point is used to either make a determination of accept-reject, or to continue.

- Sequential Sampling - This plan carries multiple sampling to the limit by using successive samples of one and comparing the accumulated number of defectives with acceptance and rejection numbers determined by formulas.

The OC curves of the sampling plans above are practically alike. A choice among them can be based on practical considerations, mainly costs of administration and actual inspection. The single sampling plan, the most commonly used, is easiest to administer with one sample, one recording, and one decision. The double plan has the advantage that on the average fewer pieces will need to be checked before a decision is reached. However, it is somewhat more difficult. The multiple plan requires even fewer pieces to be checked, on the average, but is still more complicated to administer. And as expected, sequential sampling is even more complicated to administer. And as expected, sequential sampling is even more economical on number of items tested -- sequential sampling commonly requires a third to a half fewer observations, on the average, than single sampling.

Usually the objective is to minimize the sample size in order to save the time required to reach a decision on the measurement in question. Generally a single sampling is the best choice. This is followed by double, multiple and the sequential sampling plans previously described.

There is no single perfect sampling plan, and there are many factors which should be evaluated to examine the variety of tradeoffs with exist. Some of the factors that have already been mentioned and additional factors that should be considered are:

1. What should be the acceptable quality level? Obviously zero defectives are desired and should always be the

goal of any quality control program. What level of quality can be sustained? While this consideration and its decision is not generally within the province of the QA/QC Technician, she/he should understand the nature of the factors going into the decision making process.

2. What are the resultant costs if different AQL's, producer's and consumers' risks are sought. How many more tests need be performed and what will they tell us? The OC curve shows the risks involved for given incoming quality levels under one sampling plan. Curves can be developed for any sampling scheme using tables commonly found in statistical quality control texts. From these curves the appropriate sample sizes and risks can be determined. Estimates of costs can then be found.
3. What is the level of capability required for acceptance tests? Does such capability exist either within the organization, or must an outside vendor be used?
4. What will be the impact of the decisions on having the material available for use at the time and place needed? To use rejected material, it may have to be altered, reworked, sorted or changed in design, or other parts and processes may have to be modified.

Use of MIL-STD-105D

The final concept to be considered in this section on Acceptance Inspection is the use of MIL-STD-105D in selecting and evaluating sampling plans. Many of the plans used in industry, such as in receiving inspection activities, are extracted from this publication and copied into company manuals, forms, and instructions. The publication contains, in addition to the sampling tables, many definitions and procedural elements, and includes operating-characteristic curves and tables detailing the mathematical probabilities of outcomes of the various plans. This publication should be available to the student/trainee and instructor.

The publication "Military Standard - Sampling Procedures and Tables for Inspection by Attributes" (MIL-STD-105D) details the methods by which a sampling plan is selected and provides many options. Given information about the proposed sampling plan, the student/trainee should be able to identify and list various acceptance and rejection numbers, limiting quality, etc. To illustrate this process, consider the following with reference to MIL-STD-105D:

1. Sampling Inspection Plans to choose from - Single, Double, Multiple.
2. Acceptance Standards to chose from - Normal, Reduced, Tightened.
3. Lot Size - which is the number of units of product in a lot.
4. Inspection Level - I, II, III, 5-1, 5-2, 5-3, 5-4 which determines the relationship between the lot or batch size and the sample size.
5. Acceptable Quality Level (AQL) - which is the maximum number of defects per hundred units considered satisfactory.

In this example, select items for sampling as follows:

EXAMPLE:

GIVEN:

1. Sampling Inspection Plan - Single
2. Acceptance Standard = Normal
3. Lot Size = 1500 pieces
4. Inspection Level - II
5. Acceptable Quality Level (AQL) - 4.0%

DETERMINE:

The following by reference to MIL-STD-105D:

A. Code Letter Applicable - This is determined by reference to TABLE I - Sample Size Code Letters - for a Lot Size of 1201 to 3200 and an Inspection Level II, the Code Letter will be "K".

B. Sample Size and Acceptance and Rejection Numbers - This is determined by reference to TABLE II-A - Single Sample Plans for Normal Inspection (Master Table). In the Sample Size Code Letter column see "K" and read across to the 2nd column called "Sample Size", the sample size of 125. Then read under the Acceptable Quality Level (normal inspection) column labeled "4.0", the acceptance number (AC) = 10, and the rejection number (RE) = 11.

C. Limiting Quality for which P_a (probability of acceptance) is 10 percent - This is determined by reference to Table VI-A- Limiting Quality (in percent defective) for which P_a = 10 percent. Under the "code letter" column, see code K, and read across to the AQL column "4.0" to obtain the LQ of 12. This table indicates the number of rejects (12 in this case) which are accepted by the sampling plan based on a 10% probability of acceptance level (consumer risk).

NOTE: The row of numbers on the same line as the code letter K in TABLE VI-A is obtained from a set of OC curves corresponding to the sample size code K in TABLE X-K (Chart K and TABLE X-K-1) on page 48. In Chart K (the right hand chart), we see a curve labeled with the AQL of 4.0. Reading across from the P_a - 10% in the chart, an LQ of 12 is obtained from the intersecting point on the 4.0 AQL curve. Now reading TABLE X-K-1 below the chart, the corresponding 10% P_a level

is found in the left column. By reading across that row to the AQL column labeled "4.0", the value 12.3 is found. Note that this is a more precise estimate of the LQ obtained in the previous TABLE VI-A for a P_a - 10%.

There are many other definitions, plans, procedures contained in MIL-STD-105D. The instructor will aquaint the student/trainee with any additional aspects required for specific usage in his/her location.

PROCESS CONTROL

The basis of process control is the control chart which is used as an aid in determining if variation among the items is such as would occur in random sampling from a stable population. For instance, if successive samples of discharge water from a generating plant taken at hourly intervals over a long period of time resulted in a mean temperature of $22^{\circ}C$ with a standard deviation of 0.5°, the data could be used to construct a process control chart. Assuming the variation of water temperature followed a normal curve, additional samples taken at similar intervals should follow the same pattern. If a control chart such as Figure 27-7-11 is used in which the average of 22.1° is shown, with an upper control limit (UCL) and a lower control limit (LCL) at 3 standard deviations on either side of the mean, only about 3 plotted points per 1,000, on the average, would fall outside these limits.

$$(1 - .9973)\ (1000) = (0.0027)\ (1000) = 2.7 \approx 3 \text{ sample points}$$

In the above equation, remember that three standard deviations around the mean include 99.73% of the expected samples measured (See Normal Curve section). Thus, when a point did fall outside the limits, there would be a check on the process immediately to determine if something has changed, if some explanation other than chance may be assigned. If the process is in control, "false alarms" would be obtained from 3 out of every 1,000 samples. Obviously, other control limits could be chosen to be more or less sensitive to possible changes in the process. Obviously process control does not tell whether the process itself is satisfactory, but only that it is under statistical control, and therefore, predictable.

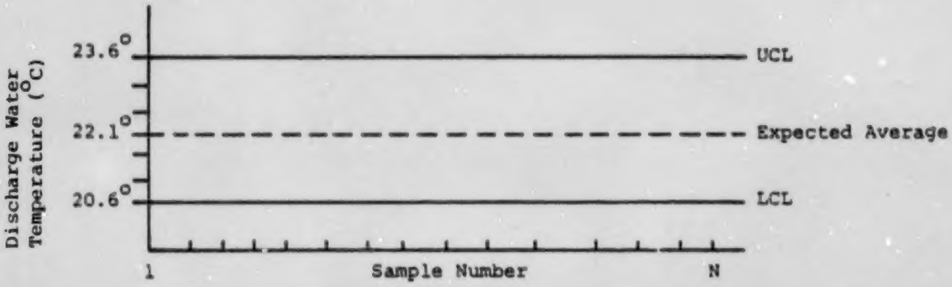


Figure 27-7-11 Upper and Lower Control Limits for Discharge Water Temperature

SUMMARY

This module presented the major points outlined below. Before proceeding to the Exercises, review each of the following major points.

1. The QA/QC Technician uses statistical techniques (a) to describe the characteristics of items such as size or weight; (b) to make decisions about acceptability of a batch of items from measurements made on a sample of items, and (c) to assess the accuracy and precision of the measuring instruments themselves.

2. No measurement is absolute due to variations from several factors including the measuring instrument and the individual making the instrument.
3. Measurements can be treated as absolute when assigned the mid-value of the measurement cell to which they belong.
4. An important characteristic of sets of data is the central tendency of the data as measured by the arithmetic mean ($\bar{x}$).
5. An important characteristic of a set of data is the dispersion of the measurements about the mean and this is measured by the standard deviation (s).
6. When large sets of measurements are made, the measurements often arrange themselves around the mean in a pattern that looks like a bell-shaped curve. The curve is also called the normal curve and it is useful in making decisions in both acceptance inspections and in process control operations.
7. Acceptance Inspection requires the selection of a sampling plan (MIL-STD-105D), which involves the taking of measurements on a lot sample and the statistical treatment of the measurements in order to accept or reject the lot.
8. Process control involves the taking of successive samples of the output of a system such as a pumping system, and applying statistical techniques to determine if the system is under control.
9. Any sampling plan involves two risks; one is the risk that a good lot will yield a bad sample (the producer's risk) and the second is that by pure chance a good sample may be drawn from a bad lot (the consumer's risk).
10. Sampling is based on randomness. The majority of sampling plans used in industry are obtained from the publication MIL-STD-105D.

11. There are four basic sampling plans encountered in practice which are based on an acceptable quality of 0.50 percent or fewer defective items in a lot. They are:
    a. Single Sampling
    b. Double Sampling
    c. Multiple Sampling
    d. Sequential Sampling

EXERCISES

In an effort to reinforce the concepts presented in this module, the following exercises have been subdivided into five sets with answer keys to each set.

Exercise Set No.	Title
1	True - False Questions on Overall Modules
2	Measurement Cell Exercises
3	Standard Deviation Exercises
4	Normal Curve Exercises
5	Statistics Exercises

1. True - False Exercise

(a) ____ Absolute measurements can be made by skilled technicians using accurate instruments.

(b) ____ A measurement cell represents an interval of uncertainty concerning true measurements.

(c) ____ Cell limits indicate the extreme upper and lower measurements possible within a measurement cell.

(d) ____ Cell intervals must be a constant length within one distribution.

(e) ____ The midpoint of a measurement cell is the most common measurement that falls within that cell.

(f) ____ Every measurement cell within a distribution will have a frequency of at least one.

(g) ____ Cell frequencies are obtained by tallying all the measurements within the distribution into the appropriate measurement cells.

(h) ____ A cell midpoint may be computed by adding the cell limits and dividing by 2.

(i) ____ A distribution always clusters around its arithmetic mean.

(j) ____ The mean is a common measure of central tendency.

(k) ____ The larger the standard deviation of a distribution, the more closely the measurements cluster around the mean.

(l) ____ A set of measurements that is normally distributed (or follows the normal curve) has many more measurements near its mean than at the extremes.

(m) ____ The total area under the normal curve is 100% of the distribution.

(n) ____ In a normally distributed set of measurements, 68.27% of the measurement will fall between two standard deviations below and two standard deviations above the mean.

(o) ____ Data that indicate whether the measurements are within or beyond some specified requirement are called attribute data.

(p) ____ The producer's risk is the probability that a bad lot will yield an acceptable sample.

(q) ____ The operating characteristic (OC) curve shows the risk involved with a particular sampling plan.

(r) ____ If cost were not considered, increasing the sample size would always be preferable.

(s) ____ When a product has a history of low acceptance, the Technician may be told to lower the acceptance standards as specified in MIL-STL-105D.

(t) ____ A control chart indicates whether a process is under statistical control.

Answers to True - False Exercises

(a) False
(b) True
(c) True
(d) True
(e) False
(f) False
(g) True
(h) True
(i) False
(j) True
(k) False
(l) True
(m) True
(n) False
(o) True
(p) False
(q) True
(r) False
(s) False
(t) True

2. **Measurement Cell Exercise**

(a) Determine the midpoints of the following measurement cells. Often you can determine the midpoint by inspection. You can also compute the midpoint of the interval (the arithmetic mean) by adding the cell limits together and dividing by 2.

(1) 10-20
(2) 500-1000
(3) 1.5-2.0
(4) 0.550-0.600
(5) 0.1050-0.1100
(6) 27.5-28.5
(7) 225-275
(8) 0.680-0.690
(9) 0.3325-0.3330
(10) 0.1020-0.1050
(11) 0.985-0.995
(12) 55.75-56.25

(b) A QA/QC person measured a sample of incoming parts and recorded the following measurements:

.4059	.4485	.4033	.4226
.4239	.4543	.4056	.4311
.4325	.4379	.4465	.4007
.4559	.4172	.4291	.4112
.4545	.4572	.4491	.4591
.4075	.4495	.4176	.4165
.4117	.4475	.4332	.4329
.4570	.4581	.4502	.4005

Complete the following table determining the cell midpoints and tallying the frequency for each measurement.

Hint: Frequency is the number of measurements that fall within a measurement cell.

The first measurement cell frequency and midpoint have been done for you.

Table for Listing Frequencies of Incoming Parts in Specified Measurement Cells

MEASUREMENT CELLS	CELL MIDPOINTS	FREQUENCIES	TALLIES
.4550-.4600	.4575	5	~~1111~~
.4500-.4550			
.4450-.4500			
.4400-.4450			
.4350-.4400			
.4300-.4350			
.4250-.4300			
.4200-.4250			
.4150-.4200			
.4100-.4150			
.4050-.4100			
.4000-.4050			

(c) Using a cell interval of .25, set up a data table like the one in Exercise 2 for the following set of measurements:

.91	.56	2.21	2.23	1.73
1.22	2.41	.65	1.85	1.24
1.59	1.05	1.43	1.56	1.29
1.91	.88	1.62	2.19	1.39
.74	1.85	2.35	1.65	.71

Hints: Note the lowest and highest value above to establish the total range of numbers. Your lowest measurement cell should have cell limits of .50-.75. The midpoint values will have 3 decimal places (.625 for the measurement cell .50-.75).

Answers to Measurement Cell Exercises

(a)
(1) 15
(2) 750
(3) 1.75
(4) 0.575
(5) 0.1075
(6) 28
(7) 250
(8) 0.685
(9) 0.33275
(10) 0.1035
(11) 0.99
(12) 56

(b)

.4550-.4600	0.4575	5	~~1111~~
.4500-.4550	0.4525	3	111
.4450-.4500	0.4475	5	~~1111~~
.4400-.4450	0.4425	0	
.4350-.4400	0.4375	1	1
.4300-.4350	0.4325	4	1111
.4250-.4300	0.4275	1	1

.4300 .4250	0.4225	3	11
.4150-.4200	0.4175	3	111
.4100-.4150	0.4125	2	11
.4050-.4100	0.4075	3	111
.4000-.4050	0.4025	3	111

(c)

MEASUREMENT CELLS	CELL MIDPOINTS	FREQUENCIES	TALLIES
2.25-2.50	2.375	2	11
2.00-2.25	2.125	3	111
1.75-2.00	1.875	3	111
1.50-1.75	1.625	5	~~1111~~
1.25-1.50	1.375	3	111
1.00-1.25	1.125	3	111
0.75-1.00	0.875	2	11
0.50-.75	0.625	4	1111

3. Standard Deviation Exercises

   (a) Use the information in the following data table to compute the standard deviation and mean of the measurements given.

Measurement Cell	Mid-Point (x)	Frequency (f)	$f \cdot x$	x^2	$f \cdot x^2$
0.30-0.35	0.325	2	0.650	0.1056	0.2112
0.250-0.30	0.275	3	0.825	0.0756	0.2268
0.20-0.25	0.225	5	1.125	0.0506	0.2530
0.15-.20	0.175	5	0.875	0.0306	0.1530
0.10-.15	0.125	4	0.500	0.0156	0.0624
0.05-.10	0.075	1	0.075	0.0056	0.0056
Sums		N=20	$\Sigma fx=4.05$		$\Sigma fx^2=0.912$

Formulas:

$$s = \sqrt{\frac{N\Sigma fx^2 - (\Sigma fx)^2}{N(N-1)}}$$

$$\bar{x} = \frac{\Sigma fx}{N}$$

(b) Complete the data table below and determine the standard deviation of the measurements given.

Measurement Cell	Mid-Point (x)	Frequency (f)	f·x	x^2	$f \cdot x^2$
0.65-0.68	0.665	3	1.995	.4422	1.3266
0.62-0.65		5			
0.59-0.62		8			
0.56-0.59		6			
0.53-.056		2			
Sums		N=____	Σfx=____		Σfx^2= ____

$$s = \sqrt{\frac{N\Sigma fx^2 - (\Sigma fx)^2}{N(N-1)}}$$

(c) Set up a data table for the following set of measurements. Use cell intervals of 5.0. The lower limit of the first measurement cell should be 0. Use the formulas:

$$s = \sqrt{\frac{N\Sigma fx^2 - (\Sigma fx)^2}{N(N-1)}}$$

$$\bar{x} = \frac{\Sigma fx}{N}$$

to determine the standard deviation and mean of the measurements.

6.1, 7.2, 11.1, 19.8, 15.3, 18.0, 13.4, 9.7, 3.5, 18.3, 12.5, 7.7, 15.3, 10.5, 6.8, 14.2, 17.7, 4.9, 23.1

(d) A QA/QC Technician had instructions to reject a shipment of bearings if the standard deviation of the weights of the bearings was greater than 0.25 milligrams. Should the technician accept or reject the shipment of bearings from which the following weight measurements were taken?

9.5, 10.3, 9.9, 10.1, 9.8, 9.7, 10.4, 10.1, 9.5, 10.2, 9.8, 9.9, 10.2, 10.0, 9.9, 10.1 (All measurements in milligrams.)

Hint: Use 5 measurement cells starting with the lowest cell of 9.5-9.7.

Answers to Standard Deviation Exercises

(a) $s = 0.0695$

(b)

MEASUREMENT CELL	MID-VALUE (x)	FREQUENCY (f)	$f \cdot x$	x^2	$f \cdot x^2$
0.65-0.68	0.665	3	1.995	0.4422	1.3266
0.62-0.65	0.635	5	3.175	0.7669	3.9845
0.59-0.62	0.605	8	4.840	0.3660	2.9280
0.56-0.59	0.575	6	3.450	0.3306	1.9836
0.53-0.56	0.545	2	1.090	0.2970	0.5940
SUMS:		N=24	$\Sigma fx=$ 14.55		$\Sigma fx^2=$ 10.8167

$$s = \sqrt{\frac{24\ (10.8167) - (14.55)^2}{24(23)}}$$

$s = 0.2946$

(c)

MEASUREMENT CELL	MID-POINT (x)	FREQUENCY (f)	f·x	x^2	$f \cdot x^2$
20-25	22.5	1	22.5	506.25	506.25
15-20	17.5	6	105.0	306.25	1837.50
10-15	12.5	5	62.5	156.25	781.25
5-10	7.5	5	37.5	56.25	281.25
0- 5	2.5	2	5.0	6.25	12.50
SUMS:		N=19	$\Sigma fx=$ 232.5		$\Sigma fx^2=$ 3418.75

$$s = \sqrt{\frac{19\ (3418.75)\ -\ (232.5)^2}{19(18)}}$$

s = 5.6455

(d)

MEASUREMENT CELL	MID-POINT (x)	FREQUENCY (f)	$f \cdot x$	x^2	$f \cdot x^2$
10.3-10.5	10.4	2	20.8	108.16	216.32
10.1-10.3	10.2	5	51.0	104.04	520.20
9.9-10.1	10.0	4	40.0	100.00	400.00
9.7-9.9	9.8	3	29.4	96.04	288.12
9.5-9.7	9.6	2	19.2	92.16	184.32
SUM:		N=16	$\Sigma fx=$ 166.4		$\Sigma fx^2=$ 1608.96

$$s = \sqrt{\frac{16\ (1608.96)\ -\ (160.4)^2}{16(15)}}$$

$s = 0.2517$

4. Normal Curve Exercises

(a) A supplier claims that the wire he produces has a mean breaking strength of 13.6 pounds with a standard deviation of 2.2 pounds. If this claim is valid:

(1) 95.45% of the wire sampled by a technician can be expected to have breaking strengths between ______________ and ______________.

(2) Only 3 out of each 1000 sample wires will have breaking strengths of less than ________________ or more than ______________.

(b) If a supplier of steel pins specifies that the pins have a mean weight of 12.4 ounces, with a standard deviation of 0.06 ounces, what percent of sample pins would a technician expect to weight a) between 12.34 ounces and 12.46 ounces? ______________ (b) between 12.22 ounces and 12.58 ounces? __________________

(c) The mean diameter of a lot of copper rods is claimed to be 16.3 millimeters with a standard deviation of 0.15 millimeters. Which of the following sample measurements are either too small or too large to fall within 99.73% of this distribution (±3 standard deviations)?

(1) 16.5
(2) 16.25
(3) 16.8
(4) 16.18
(5) 16.63
(6) 15.63
(7) 16.79
(8) 16.35
(9) 16.12

(d) Measure the major diameters of a box of 100 machine bolts (see Procedures section of this module) (UNC coarse or fine thread) using an outside micrometer and tabulate the data on the table in the Data Table section of this module. Using these data plot a Normal Curve for the distribution of bolt diameter and explain its shape.

Answers to Normal Curve Exercises

(a) (1) 9.2 and 18 pounds
(2) less than 7 or more than 20.2 pounds

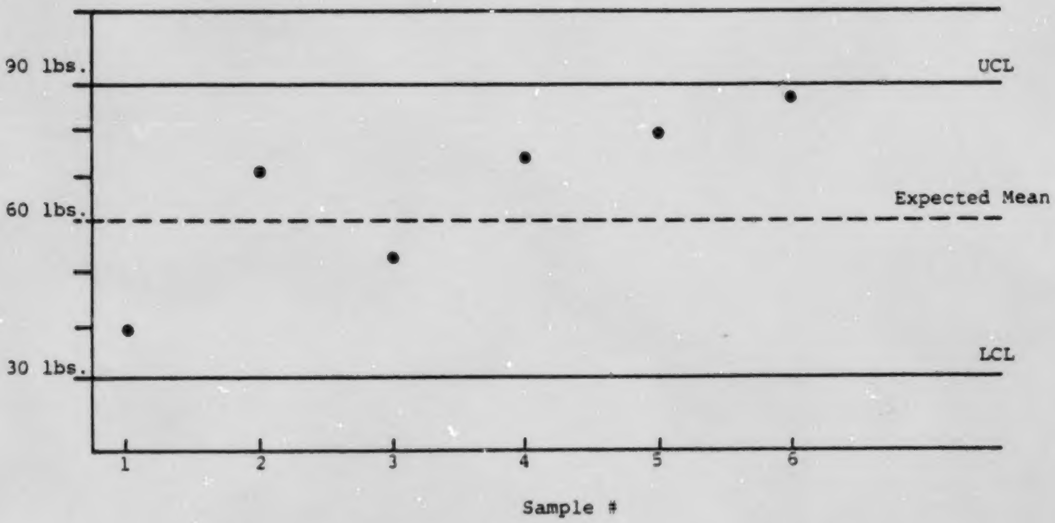
(b) (1) 68.27%
(2) 99.73%

(c) (1) 16.8 (too large)
(2) 15.63 (too small)
(3) 16.79 (too large)

(d) Refer to Procedures section of this module.

5. Statistics Exercise

(a) The following control chart records sample pressure readings of a storage tank.



(1) According to the six samples in the chart, is the process in control?

(2) What is the standard deviation that was used to set the UCL and LCL?

(3) How many pressure readings were above the mean?

(4) What reading was obtained on the 4th. sample?

(b) Construct a control chart for the following data obtained from repeated measurement of pollutants in samples of air. The expected mean is 50 particles per 1000 with a standard deviation of 5.

Sample #	Pollutants Per 1000 Particles
1	52
2	54
3	53
4	59
5	51
6	45
7	47
8	58
9	64
10	67

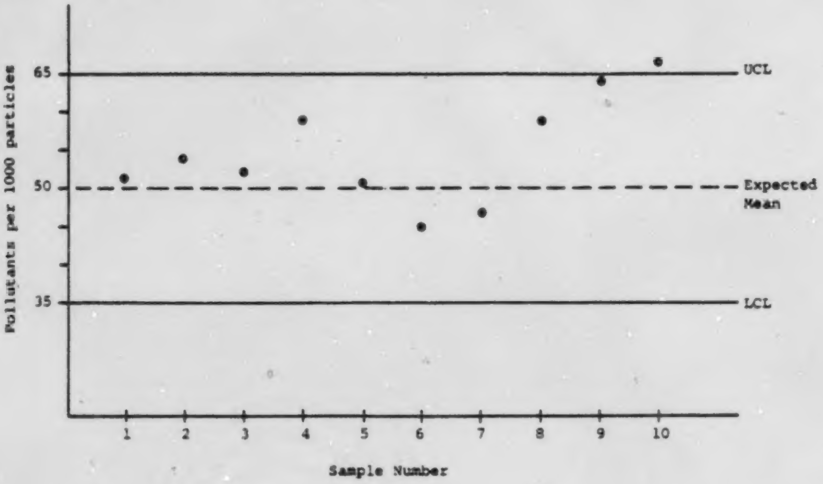
(1) Does the control chart assure the technician that the process is in control?

(2) Which sample reading(s) might lead the technician to check on the process?

Answers to Statistics Exercises

(a) (1) Yes
    (2) 10 pounds
    (3) 4
    (4) 80 pounds (approximately)

(b) Plot:



(1) Yes

(2) Sample 10

MATERIALS

The following materials will provide the student and instructor with additional support in working on the Exercises and carrying out the Procedures listed in this module.

1. Hand Calculator
2. Quality Control textbook (see Reference Materials).
3. Outside Micrometer (one inch)
4. Box of machine bolts (minimum of 100 bolts of UNC) coarse or fine threads.

PROCEDURES

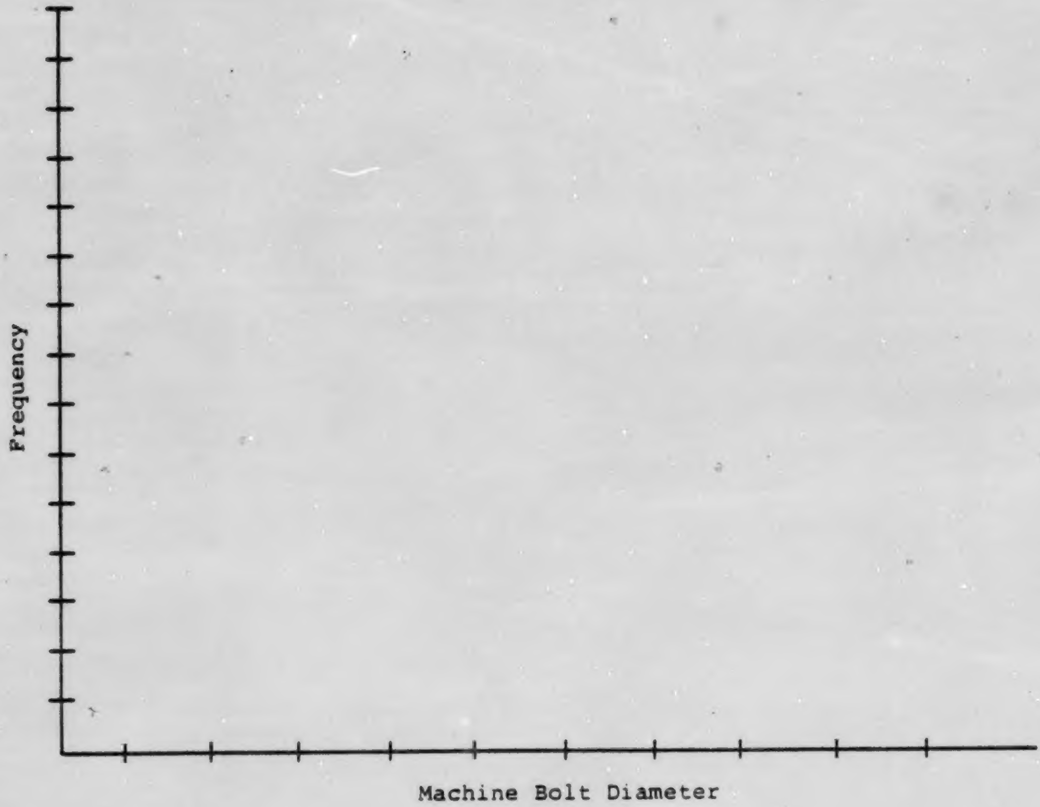
1. Measure the major diameter of a box of 100 machine bolts (UNC coarse or fine thread) using an outside micrometer.
2. Tabulate these data on the data table provided in the Data Table section which follows.
3. Plot the results on a graph of frequency (machine bolt number) vs. major diameter to obtain a normal distribution for these data. The graph is given in the Data Table section which follows.
4. Explain the shape of the normal distribution you have plotted and label the graph for one, two and three standard deviations.

DATA TABLE

Table 27-7-2
Machine Bolt Major Diameter

Machine Bolt Number	Major Diameter	Machine Bolt Number	Major Diameter	Machine Bolt Number	Major Diameter	Machine Bolt Number	Major Diameter
1		26		51		76	
2		27		52		77	
3		28		53		78	
4		29		54		79	
5		30		55		80	
6		31		56		81	
7		32		57		82	
8		33		58		83	
9		34		59		84	
10		35		60		85	
11		36		61		86	
12		37		62		87	
13		38		63		88	
14		39		64		89	
15		40		65		90	
16		41		66		91	
17		42		67		92	
18		43		68		93	
19		44		69		94	
20		45		70		95	
21		46		71		96	
22		47		72		97	
23		48		73		98	
24		49		74		99	
25		50		75		100	

Table 27-7-3
Graphical Plot of Data from Machine Bolt Major Diameter Measurement from Table 27-7-2



REFERENCE MATERIALS

Duncan, A.J. *Quality Control and Industrial Statistics*,
Homewood, Ill.; Richard D. Irwin, Inc., 1965

Juran, J.M., Gryna, F.M., Jr., and Bingham, R.S., Jr. Eds.,
Quality Control Handbook. New York. McGraw Hill, 1974.

Military Standard. *Sampling Procedures and Tables for Inspection by Attributes* (MIL-STD-105D). Washington, DC.:
Department of Defense, 29 April 1963.

TEST

Read each question carefully. Be sure to provide the specific information each question requires. Make your answers brief. Use the backs of the test if you need more space.

1. Determine the midpoint of the following measurement cells.
   a. 0.650-0.660
   b. 0.1050-0.1100
   c. 0.285-0.295
   d. 55.75-56.75

2. Determine the measurement cell limits for each of the following inspection activities:
   a. Measurement of 1.125 dimension to nearest 0.001 inch.
   b. Measurement of 0.1250 dimension to nearest 0.0005 inch.
   c. Measurement of 125.75 dimension to nearest 0.002 inch.

3. Using a measurement cell interval of 0.002 and 0.4460-0.4480 as lowest measurement cell, set up a data table showing measurement cells, frequencies, and cell midpoints for the following inspection results (use the table below for recording the data).

0.4478	0.4495	0.4555	0.4568	0.4514
0.4461	0.4501	0.4545	0.4508	0.4496
0.4483	0.4509	0.4573	0.4492	0.4525
0.4482	0.4525	0.4566	0.4502	0.4486

Measurement Cells	Frequencies	Cell Midpoints

4. Compute the mean of each set of numbers (give answers to one additional decimal place than used in each set)

a. 26, 32, 28, 42, 37, 33

b. 0.448, 0.450, 0.445, 0.458, 0.460, 0.442, 0.445

c. 0.025, 0.030, 0.018, 0.022, 0.024, 0.028, 0.029, 0.027

5. Complete the data table below and determine the standard deviation of the measurements given using the formula.

$$s = \sqrt{\frac{N\Sigma fx^2 - (\Sigma fx)^2}{N(N-1)}}$$

Give each answer to three decimal places.

Measurement Cell	Mid-Value x	Frequency f	$f \cdot x$	x^2	$f \cdot x^2$
0.235-0.245		2			
0.225-0.235		3			
0.215-0.225		5			
0.205-0.215		5			
0.195-0.205		2			
Sums		$N =$	$\Sigma fx =$		$\Sigma fx^2 =$

Standard Deviation =

6. Describe each of the following sample plans.

a. Single sampling: ______________________________

____

____

____

b. Double sampling: ______________________________

____

____

____

c. Multiple sampling: ______________________________

____

____

____

7. Give one advantage and one disadvantage for each of the following sampling plans.

a. single sampling:

advantage: ______________________________

____

disadvantage: ______________________________

____

b. double sampling:

advantage: ______________________________

____

disadvantage: ______________________________

____

c. multiple sampling:

advantage: ______________________________

____

disadvantage: ______________________________

____

8. Describe producer's risk.

____

____

____

____

9. Describe buyer's risk.

____

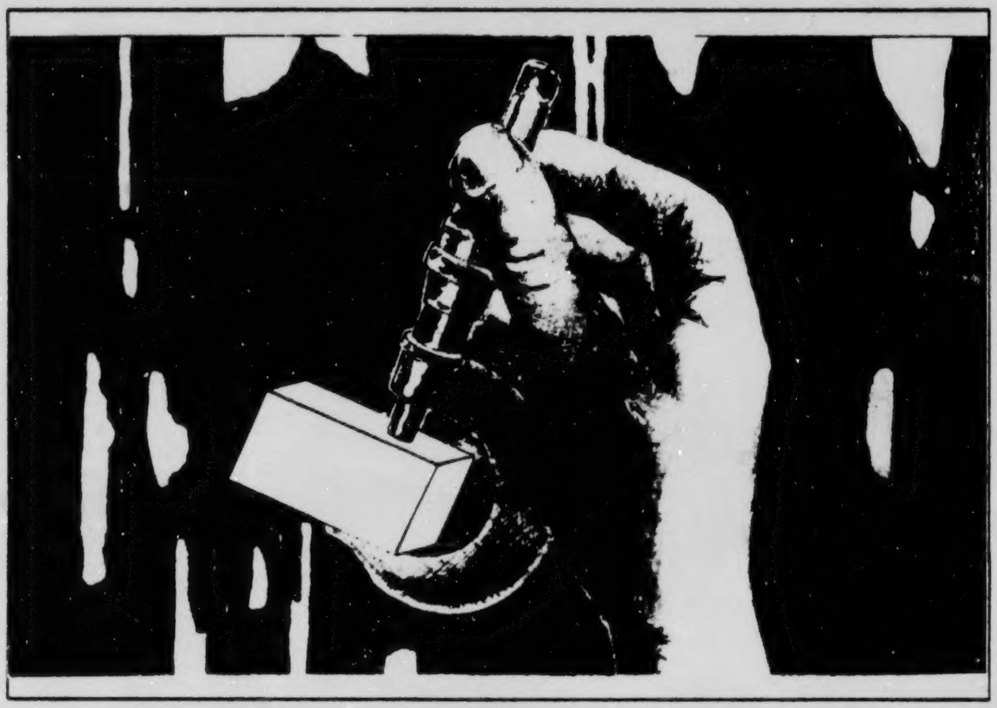
____

____

NUCLEAR TECHNOLOGY

MODULE 27 - 8

THE TOTAL MEASUREMENT SYSTEM



COURSE 27: METROLOGY

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
4800 LAKEWOOD DRIVE WACO, TEXAS

COURSE 27 METROLOGY

MODULE 27-1	Fundamentals of Metrology
MODULE 27-2	Fixed Gages, Dividers, Calipers and Micrometers
MODULE 27-3	Gage Blocks, Mechanical Comparators and Electronic Comparators
MODULE 27-4	Angle Measurement Instruments, Optical Projectors and Surface Texture Gages
MODULE 27-5	Tolerancing
MODULE 27-6	Calibration
MODULE 27-7	Statistical Techniques in Metrology
⇨ MODULE 27-8	The Total Measurement System

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INTRODUCTION

Course 31, Quality Assurance Practices, describes eighteen elements of a Quality Assurance Program applicable to a nuclear power plant as required by Title 10, Code of Federal Regulations, Part 50 (10CFR50). Three of the eighteen Quality Assurance Criteria specified by 10CFR50 apply to Metrology. The titles of these three criteria and a condensed statement of each are as follows:

- Criterion X, Inspection - A program of inspections is required to verify conformance of product with specified requirements.
- Criterion XI, Test Control - A program of testing is required to demonstrate that structures, systems, and components will perform satisfactorily in service.
- Criterion XII, Control of Measuring and Test Equipment - Measures are required to control, calibrate and adjust at specified periods measuring and testing devices used in activities affecting quality.

This module describes the overall metrology program and the associated typical responsibilities of the QA/QC Technician. Specifically, QA/QC Technician responsibilities in the following areas are addressed:

1. Inspectability during the design phase.
2. Inspection staging during the manufacturing phase.
3. Inspection planning.
4. Establishment of policies and procedures.
5. Criteria for evaluating any portion of inspection and calibration activities.

MODULE PREREQUISITES

The student/trainee shall have completed all previous modules of this course.

OBJECTIVES

Upon completion of this module, the student/trainee shall be able to:

1. Differentiate between inspection and inspectability and state the role each has in metrology.
2. Define inspection staging and describe its role.
3. List six criteria for inspection staging and describe the application of each.
4. List six elements of inspection planning, state the purpose of each, and describe typical applications of each.
5. State the purpose of inspection policies, inspection procedures and inspection instructions.
6. Apply the concept of S.W.I.P.E. to an inspection or calibration function.

NOTES TO INSTRUCTOR / STUDENT

This module is designed primarily for instruction by classroom lecture. It recommends one laboratory exercise for applying the concept of S.W.I.P.E. The Acronym S.W.I.P.E. was defined by Mary Hoskins, a noted metrologist and contains the following important factors relevant to dimensional metrology:

S = STANDARD
W = WORKPIECE
I = INSTRUMENT
P = PERSON
E = ENVIRONMENT

Each of the above factors as related to dimensional metrology have been considered in some detail in the previous modules of this couse. In this module it will be noted that advance preparation will be necessary to select procedures for students/trainees to evaluate using the S.W.I.P.E. concept.

INSPECTABILITY

Definitions and Role

Inspection and inspectability are defined as follows:

- Inspection - Inspection is the art of critically examining parts by someone other than the producer of the part and with the aid of suitable standards and measuring devices which confirm or deny to the observer that the particular item under examination is within the specified limits of variability.
- Inspectability - Inspectability is the condition of the part which allows inspection to be performed.

As defined, inspection results in acceptance or rejection of the product. Inspection involves the examination to determine if material or work performed is according to specifications and it verifies whether the material or work conforms to a standard. To provide for unbiased objectivity, inspection is normally performed directly by or under the cognizance of the QA/QC Department, as opposed to manufacturing or maintenance departments. However, inspection defined in this manner is never intended to relieve in any way the responsibility of the manufacturing and maintenance departmens to produce an acceptable product. Instead, the role of inspection is to measure the effectiveness of the product of conforming parts by the manufacturing or maintenance department.

Inspectability applies to both design activities and staging during manufacturing. Its role is to ensure that a given design is capable of being inspected and to stage the inspection activity at a point in manufacturing which provides capability of inspection.

Inspectability During Design

In its broadest sense, inspectability encompasses review of designs to determine if product features can be inspected and also review of measuring devices and practices to determine if adequate equipment and skills are available to perform inspection. In either case, the knowledge and experience of the inspection activity can prevent problems during manufacturing, construction, testing, operations and maintenance phases if good communications exist between engineering and inspection activities. Typical means of communication include the following:

- Scheduled meetings to periodically review concerns and exchange information.
- Unscheduled meetings to review concerns as the need arises.
- Independent design reviews by a task force to determine, among other things, the inspectability of the design.

The Quality Assurance Manager normally has lead responsibility for communicating with engineering. The QA/QC Technician supports the QA Manager by conducting investigations, studies, special reviews, etc., to supply information pertaining to inspectability. Such information is important for review of designs initially and for subsequent feedback to engineering on the results of the manufacturing, construction, and maintenance plans. Such later feedback helps engineering to improve subsequent designs. The evaluation criteria described later in this module should assist the QA/QC Technician in accomplishing this supportive role.

INSPECTION STAGING

Definition and Purpose

Inspection staging is defined as the process of matching the point of inspection with the appropriate manufacturing step. Its purpose is to ensure that inspection is performed at a point where inspectability exists but where any later manufacturing steps will not affect the inspection results.

Types of Inspection Staging

Manufacturing, construction and maintenance activities are accomplished in accordance with pre-established instructions. Such instructions may be a simple listing of processing steps such as, (1) saw, (2) machine, (3) clean and, (4) inspect. Or they may involve detailed instructions on each processing step. The complexity of the work processes and the governing codes and regulations determine the detail contained by manufacturing, construction and maintenance instructions. Regardless of detail, a determination is needed to establish the points of manufacturing, construction, or maintenance where inspection will occur. Such determination is made by engineering or quality assurance/ quality control or both. Such determination is made for two types of inspections: in-process and final.

In-process inspection serves to assist the manufacturing, construction, or maintenance activity to produce an acceptable product. It is typically employed with the following activities:

- Layout - Layout involves the establishment of datums or base line information from which initial machining, assembly, or other processing operations can obtain a reference origin. For complex layouts, the inspection activity either performs the layout or checks the layout made by another group.

Layout is actually the opposite of inspection, which was discussed previously. Layout is the preparation of material so that work can be performed according to specifications, whereas inspection was described as the examination to determine whether material or work performed in according to specifications.

Layout typically refers to scribing lines to show limits for milling, grinding, or band machining, and the location of centers or diameters to be drilled, turned or bored. The layout furnishes a guide, but the precision of the machine tool determines the actual dimensions. The layout limits the precision of the machining. A part may be ruined by bad machining regardless of the care used in layout. However, if the layout is in error, the part will not comply to specifications no matter how carefully it was machined.

- Setup - Many machining, welding, and assembly processes involve complex setups which position the part and tooling correctly with respect to layout datums or previously machined datums. The datum is an assumed level surface used as a reference surface for the measurement of reducing levels with respect to that surface. The inspection activity typically inspects the initial setup and rechecks it as each shift change.
- Production - A roving, random inspection activity is frequently employed to spot check manufacturing, construction, or maintenance processes to gain assurance of continued production of acceptable product. Process control charts employing the statistical analysis techniques described by Module 27-7 are sometimes

employed with such in-process inspection. Where final inspection is impossible after completion of processing statistical in-process inspection also serves to verify acceptability in lieu of final inspection.

Final inspection serves to determine acceptability of product. Individual product features may be accepted based on a sampling inspection described by Module 27-7 or based on 100% inspection. Final inspection means inspection for acceptance purposes. It is not necessarily performed after all processes have been completed. In many cases, final inspection must be staged at discrete points of manufacture, construction, or maintenance in order to satisfy the predominant inspection staging criteria.

Criteria for Inspection Staging

As implifed by its name, in-process inspection requires planning for the stages of manufacture, construction, or maintenance at which the inspection will occur. Similar planning is needed for final inspection. Criteria governing such planning are listed in Table 27-8-1.

Referring to Table 27-8-1, criterion #1 is the basis for employing layout inspection. Such inspection can reduce the rework and repair costs by ensuring correct establishment of initial reference datums. Criterion #2 is the basis for both setup and roving inspection in-process. Again, its purpose is to reduce rework and repair costs. Criterion #3 is a basis for both in-process and final inspection. Since the datum will be referenced in the manufacture of other features, its accurate generation is important to both reduce rework and repair costs as well as for product acceptance. Criteria #4 and #5 are the basis for performing final inspection at an in-process point of manufacture, construction, or maintenance. These criteria demand inspectability

Table 27-8-1

CRITERIA FOR INSPECTION STAGING

Criterion	Applicable To	
	In-Process	Final
1. Establishment of a datum to support initial machining. Such datums result from layout and may be center points, center lines, reference indexing points or lines, true position layout points or lines, reference notches or grooves.)	X	
2. Establishment of a final feature which can be inspected after all processing is completed but which has a relatively high associated risk of nonconformance. (Examples include those critical features upon which function and fit are predicated and which involve difficult or complex manufacturing, construction, or maintenance steps. Discovery of a number of nonconforming parts with such features probably means a large rework or repair cost. Size, form, and position of mating surfaces, holes, threads, pins, nozzles, seals, supports, bearings and mounts are candidates for such critical features.)	X	
3. Establishment of a datum feature referenced by subsequent manufacturing, construction, or maintenance steps. (Such datum features may be surfaces or axes.)	X	X
4. Establishment of a final feature from a datum where such datum will be removed or modified by subsequent processing. (Such cases normally involve the need for a datum from which to index the machine where the final part does not require such a datum.)		X
5. Establishment of a final feature which will be made inaccessible by later processing. (Examples include size, location or form limits which are applicable prior to plating, painting welding or assembly.)		X
6. Features accepted by final inspection must not be altered by subsequent manufacturing, construction, or maintenance.		X

for final inspection. For either criterion, subsequent processing makes final inspection impossible. Criterion #6 prohibits premature application of final inspection by criteria #4 and #5.

INSPECTION PLANNING

Purpose

Inspection planning means the establishment of a predetermined scheme for inspection of product. Each company plans its inspection activity based on its liability. For example, a nuclear utility, who purchases components for installation by the construction contractor, develops inspection plans focused on those few significant product features which involve function of the component and interfacing with other components. The manufacturer of the component develops inspection plans for the many features which must be correct to permit assembly, function, and installation. Regardless of the focus of such planning, inspection planning has the purpose of ensuring the accomplishment of inspection of important product features at the correct point of manufacture, construction, or maintenance.

Elements of Inspection Planning

Inspection planning results in instructions for the inspection activity. The detail of such instructions varies among companies dependent on the management policies, the complexities of the inspections, the qualifications of the inspectors, and the requirements of codes, standards, and regulations. Nonetheless, inspection planning must generally encompass designation of features, establishment of notification selection of instruments, special instructions, acceptance criteria, and records. The QA/QC Technician may perform inspection planning or may assist a quality engineer in inspection planning.

- Designation of Features - This portion of inspection planning designates what will be inspected. The specific features selected is a function of the purposes of the inspection. The planner reviews engineering drawings and components or system codes and specifications and selects those product features important to fit, function, and interchangeability. Such features are normally documented by the planner as an inspection check list which is issued to the inspectors. A sample inspection check list is given in Appendix A.
- Establishment of Notification - This portion of inspection planning ensures that the inspection force is afforded the opportunity to inspect the designated features. It coordinates the manufacturing, construction, or maintenance activity with the inspection activity. Notification must encompass both in-process and final inspection and coincide with the staging of such inspection. Notification may be established in basically two ways. Either the processing is arranged such that the product must physically move to inspection stations at appropriate times or processing paper work accompanying the product requires oral notification to inspectors at designated processing steps. Except for some manufacturing activities, the latter approach is generally used. For the latter approach, the planner reviews the processing instructions governing the manufacturing, construction, or maintenance and marks those processing steps at which inspectors are to be notified. When the planner knows that inspection must absolutely be performed at some point, that point is marked as "hold for in-

spection". At hold points, processing stops until the corresponding inspection is performed.

- Selection of Instruments - When specific measuring instruments are necessary to inspect the designated features, the planner identifies such instruments normally on the inspection check list. When the level of inspector qualification represents skill and experience sufficient for proper selection of a measuring instrument, the planner need not specify the inspection instrument. The line of demarcation in the planner's practice is normally associated with whether special purpose instruments are demanded by the type of feature and its tolerance. For example, a special gage, consisting of fixturing and dial indicators and made for measuring runout of a certain rotor, would be referenced by the inspection check list for that rotor. The planner also determines if devices are on hand which are capable of inspecting designated features. If not, they are ordered. If suitable instruments are not on the market, the planner consults with the designer and either the design is changed or a special purpose gage is designed and built to perform the inspection.
- Special Instructions - This portion of the planning determines if special conditions apply to inspection of any of the designated features. Such special conditions may be, (1) use of sampling plans, (2) temperature and/or humidity controls, (3) specific inspection techniques, or (4) specific actions such as notifications and records not covered by other applicable procedures.

- Acceptance Criteria - This portion of the planning either identifies the document(s) which gives acceptance criteria or spells out the specific acceptance criteria. Identification of documents which give acceptance critieria has the advantage of not requiring a change to the inspection planning documentation when changes occur to the documents containing acceptance criteria. However, it has the disadvantage of requiring controlled distribution of acceptance documents to the inspection activity. Since drawings give or reference all acceptance criteria for dimensional inspection, the inspection check list normally references the drawing rather than listing tolerances for the designated features. The drawing control system described by Course 31 is relied upon to place the correct drawing at the point of inspection.
- Records - This portion of inspection planning determines the type and nature of records to be completed by the inspection function. As described in Course 31, Quality Assurance Practices, final inspection records must be retained to preserve information on the as-built condition of structures, systems, and components. The planner must decide if the record entry will be a simple indication of acceptability (such as a check mark and the inspector's signature) or the actual measured value. Governing codes, specifications, and regulations are reviewed to make this determination. The record format may take any of the following forms:
  - Entries on the corresponding processing instructions employed by manufacturing, construction, or maintenance.
  - Entries on the inspection check list.

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- Entries on a special form designed specifically for recording inspection results.
- Entires on a drawing or layout document used as an inspection record.

INSPECTION POLICIES AND PROCEDURES

Summary Review

The science of measurement, i.e., metrology, as applied to dimensions, is employed to ensure that size, form and position of product features comply with design requirements. It embraces design, manufacturing, construction, maintenance, inspection, and calibration.

- Design activities are concerned with clearly specifying and tolerancing intended sizes, forms and positions and ensuring inspectability of such features.
- Manufacturing, construction and maintenance are concerned with producing, installing, and repair product in conformance with design requirements.
- Inspection concerned with confirming the acceptability of features important to fit, function, and interchangeability.
- Calibration provides traceable measuring instruments of known accuracy for use by manufacturing, construction, maintenance and inspection activities.

The ingredient which gels these concerns into a working system are the management policies and procedures which define responsibilities establish the methods of implementing the principles with metrology.

Inspection Policy

The purpose of a written inspection policy is to advise all department heads within a company of the inspection concepts adopted by senior management of the company. Inspection policy is normally documented as a portion of the company's Quality Assurance Manual. A typical statement of inspection policy is given in Appendix B.

Inspection Procedures

Inspection Procedures implement inspection policy. These procedures typically assign responsibilities to appropriate managers and delineate the extent of inspection planning to be performed. Such procedures also establish responsibilities and practices for the calibration program (see Module 27-6). The QA/QC Technician may be responsible for assisting in the preparation of inspection procedures. A typical inspection procedures on inspection planning is given in Appendix C.

Inspection Instructions

Inspection instructions provide detailed instructions on specific functions required by inspection procedures. Such instructions are employed for those functions so important or so complex as to require written instructions for their satisfactory accomplishment. The QA/QC Technician may be responsible for preparation and maintenance of inspection instructions. Typically, written instructions are comprised of:

- inspection check lists
- records formats and corresponding instructions for their completion
- calibration procedures

EVALUATION OF INSPECTION AND CALIBRATION ACTIVITIES

The QA/QC Technician can be involved with any of the facets of dimensional metrology described by this course. In each area of involvement, the typical job tasks require evaluation of a number of factors to determine the best inspection or calibration practice or to locate error sources in measurements or calibrations. The various modules of this course have collectively presented the principles, elements and capabilities of the metrology program. Such information should serve as a good foundation for performing QA/QC Technician's tasks related to dimensional metrology. Regardless of the specification task, factors presented below serve as a helpful check list in evaluating any facet of the metrology program.

Mary Hoskins, a noted metrologist, has published a paper entitled "Taking a S.W.I.P.E. at Metrology". This paper presents pertinent factors to consider in any evaluation of procedures and practices within the metrology program. The acronym S.W.I.P.E. is defined and its factors are given below:

The acronym S.W.I.P.E. stands for:

S = STANDARD
W = WORKPIECE
I = INSTRUMENT
P = PERSON
E = ENVIRONMENT

- Factors affecting the STANDARD:
  - a. Traceability
  - b. Geometric Compatability
  - c. Coefficient of Thermal Expansion

d. Calibration Interval

e. Stability

f. Elastic Properties

g. Position of Use -- Airy Points

- Factors affecting the WORKPIECE:
  - a. Geometric Truth -- Hidden Geometry
  - b. Related Characteristics, such as Surface Finish Waviness, Scratch Depth
  - c. Elastic Properties
  - d. Cleanliness
  - e. Surface Defects
  - f. Thermal Equalization
  - g. Mass Affecting Elastic Deformation
  - h. Truth of Supporting Features
  - i. Clear Definition of Characteristic to be Measured
  - j. Adequate Datums on the Workpiece
- Factors affecting the INSTRUMENT:
  - a. Adequate Amplification for Accuracy Objective
  - b. Amplification Checked Under Conditions of Use
  - c. Effects of Friction, Backlash, Hysteresis, or Drift
  - d. Electric, Optical, or Pneumatic Input to Amplifying System Functioning Within Prescribed Limits
  - e. Contact Geometry Correct for both Workpiece and Standard
  - f. Contact Pressure Control Functioning Within Prescribed Limits
  - g. Contacts in Correct Geometrical Relationship and Inspected for Wear or Chipping
  - h. Slides, Ways, or Moving Elements Not Adversely Affected by Wear or Damage

i. Deformation Effects in the Instrument When Heavy Workpieces are Measured
j. Auxiliary Elements (such as Wires, Rolls, Angles, Plates) Calibrated and Checked for Function
k. Magnification of Errors by Contract Geometry
l. Repeatability and Readability Adequate for Accuracy Objective

- Factors affecting the PERSON:
  a. Training
  b. Skill
  c. Sense of Precision Appreciation
  d. Complacent or Opinionated Attitudes Towards Personnal Accuracy Achievements
  e. Open-Minded Competent Attitudes Towards Personal Accuracy Achievements
  f. Planning Measurements Techniques for Minimum Cost, Consistent With Precision Requirements
  g. Appreciation of Scope of Accuracy Evaluation
  h. Ability to Select High-Quality Measuring Instruments and Standards With Required Geometrical and Precision Capabilities
  i. Sensible Appreciation of Measurement Costs
- Factors affecting the ENVIRONMENT:
  a. Standard Length-Measuring Temperature is 68°F; (20°C.); for Electrical Measurements, it is 25°C or 28°C. For pressure measurements it is 23°C.
  b. Temperature Equalization Between Standard, Workpiece, and Instrument; Deficiency of One Degree in Equalization Could Introduce in Steel an Error of 6.5 Millionths Inch per Inch of Length
  c. Thermal Expansion Effects Due to Heat Radiation From Lights, Heating Components, Sunlight, and People

d. Effects of Cycles in Temperature Control
e. Impinging Drafts of Air Which May Introduce Thermal Expansion Size Errors
f. Manual Handling May Introduce Thermal Expansion Errors; Human Body Temperature is 30°F Higher Than Standard Measuring Temperature; For One-Inch Length of Steel, This Could Cause Error up to 0.0002 Inch
g. Clean Surroundings and Minimum Vibration Enhance Precision
h. Adequate Lighting
i. Atmospheric Refraction Effects in Optical Measuring Systems (air density, humidity, pressure, temperature).
j. Thermal Gradients, Either Vertical or Lateral, in the Measuring Area

EXERCISES

. Discuss the meaning of the terms inspection and inspectability regarding the examination of parts for the purpose of acceptance.
2. Explain how QA/QC communication with design activities of a project serves to ensure inspectability.
3. Explain the process of inspection staging and identify how maximum benefit is obtained in the form of lower rework and repair costs.
4. Discuss what is meant by process inspection.

5. List and briefly discuss the six criteria which govern the decisions on inspection staging as discussed in this module.
6. Inspection planning ensures the accomplishment of staged inspections and it consists of:
    a. designation and features
    b. establishment of notifications
    c. selection of instruments
    d. special instructions
    e. acceptance criteria
    f. records

    Briefly explain each of the components of inspection planning.
7. The concepts of S.W.I.P.E. offers a check list for evaluating metrology tasks to ensure consideration of factors effecting accuracy and precision of measurements and calibration. Briefly explain each of the components identified by this acronym.
8. Apply the concept of S.W.I.P.E. to an inspection or calibration procedure as identified in the Procedures Section of this module.

MATERIALS

Obtain an inspection or calibration procedure which can be used to carry out an exercise to apply concept of S.W.I.P.E. as discussed in this module.

PROCEDURES

Given an inspection or calibration procedure, evaluate the effectiveness of the procedure in terms of how well it ensures accuracy and precision. The evaluation should check each factor listed under S.W.I.P.E. The evaluation should result in a report which identifies recommended changes to the procedure for improving its effectiveness. The basis for each recommended change should be given.

DATA TABLE

Not Applicable.

REFERENCE MATERIALS

Farago, Francis T., PhD, Handbook of Dimensional Measurement, Industrial Press Incorporated, Third Printing, 1968.

Hoskins, Mary E., "Taking a S.W.I.P.E. at Metrology", Presented at Merging Metrology Conference, Hartford, Connecticut, November, 1968.

Juran, J.M., Quality Control Handbook, McGraw-Hill Book Company, New York, New York, Third Edition, 1974.

Society of Manufacturing Engineers (SME), Handbook of Industrial Metrology, Prentice-Hall, Incorporated, 1967.

TEST

Read each question carefully, Be sure to provide the specific information each questions requires. Make your answers brief as possible.

1. Differentiate the concepts of inspection and inspectability.

2. Describe the role of inspectability.

3. Define inspection staging.

4. Describe the role of inspection staging.

5. Name six criteria of inspection staging and for each state if it applies to inprocess or final inspection.

a.

b.

c.

d.

e.

f.

6. What is the purpose of inprocess inspection?

7. Name six elements of inspection planning and state the purpose of each.

Element	Purpose
a.	
b.	
c.	
d.	
e.	
f.	

8. What is the purpose of Inspection Policy?

9. What is the purpose of Inspection Procedures?

10. What is the purpose of Inspection Instructions?

11. Complete this statement. The acronym S.W.I.P.E. stands for?

S =
W =
P =
I =
E =

12. Describe how the factors of S.W.I.P.E. are used to the QA/QC Technician.

APPENDIX A

INSPECTION CHECK LIST

Item: HPS Hangers Project: Unit #1

Drawing: 46 HPS G02103 Part No.: 201.8

Acceptance Criteria: Per drawing and purchase order 619

Prepared By: I. M. Perfect (Inspection Planner) Approved By: U. R. Right (Project Engineer)

Characteristics To Be Inspected	Drawing Zone	Special Instructions
Material Certification	Note 3	1. All inspections are to be performed at receiving
Item Identification and Marking	Note 6	2. Use gage H-101 for functional check of 5.985 radius
Cleanliness	Note 8	3. Record results on Form QCI-1 per QCP 16.2
0.385 ± Diameters (4)	D-8, E-8	
True Position 0.385 Diameter (2 Places)	D-8, E-8	
Perpendicularity 0.385 Diameter (4 Places)	D-8, E-8	
5.985 Radius (Functional Check)	D-4	

APPENDIX B

NUCLEAR QUALITY ASSURANCE MANUAL	Section: 5.10 Page: 1 Revision: 0 Date: April 19, 1978 Approved:
Subject: INSPECTION VOLUME I	

QAP Ref.

5.10.0 INSPECTION

5.10.1 CRITERION X OF 10CFR50 APPENDIX B STATES:

"A PROGRAM FOR INSPECTION OF ACTIVITIES AFFECTING QUALITY SHALL BE ESTABLISHED AND EXECUTED BY OR FOR THE ORGANIZATION PERFORMING THE ACTIVITY TO VERIFY CONFORMANCE WITH THE DOCUMENTED INSTRUCTIONS, PROCEDURES, AND DRAWINGS FOR ACCOMPLISHING THE ACTIVITY. SUCH INSPECTION SHALL BE PERFORMED BY INDIVIDUALS OTHER THAN THOSE WHO PERFORMED THE ACTIVITY BEING INSPECTED. EXAMINATIONS, MEASUREMENTS, OR TESTS OF MATERIAL OR PRODUCTS PROCESSED SHALL BE PERFORMED FOR EACH WORK OPERATION WHERE NECESSARY TO ASSURE QUALITY. IF INSPECTION OF PROCESSED MATERIAL OR PRODUCTS IS IMPOSSIBLE OR DISADVANTAGEOUS, INDIRECT CONTROL BY MONITORING PROCESSING METHODS, EQUIPMENT, AND PERSONNEL SHALL BE PROVIDED. BOTH INSPECTION AND PROCESS MONITORING SHALL BE PROVIDED WHEN CONTROL IS INADEQUATE WITHOUT BOTH. IF MANDATORY INSPECTION HOLD POINTS, WHICH REQUIRE WITNESSING OR INSPECTING BY THE APPLICANT'S DESIGNATED REPRESENTATIVE AND BEYOND WHICH WORK SHALL NOT PROCEED WITHOUT THE CONSENT OF ITS DESIGNATED REPRESENTATIVE ARE REQUIRED, THE SPECIFIC HOLD POINTS SHALL BE INDICATED IN APPROPRIATE DOCUMENTS."

5.10.2 Nuclear Quality Assurance Program assures quality through inspections, checks, reviews, surveillance and audits of its agents' and suppliers'/contractors' isnpections. Requirements for inspections that are performed during the design and construction phase are an inherent part of specifications established by supplier/contractor requirements. Agents and suppliers/contractors are required to establish and implement approved written inspection programs to verify conformance with requirements in procurement documents. These programs must be consistent with Nuclear Quality Assurance Program-Design and Construction and approved by the Manager, Quality Assurance.

5.10.3 Procedures for the control of activities which affect quality shall include documented inspection requirements. The Manager, Quality Assurance is responsible for approving the QA aspects of inspection procedures as required to implement the Nuclear Quality Assurance Program-Design and Construction.

5.10.4 These procedures are provided to define the necessary inspections which are required to assure the following:

5.10.4.1 An appropriate inspector evaluation/qualification program is established.

5.10.4.2 Inspection personnel are independent of the individual or group performing the activity being inspected.

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5.10.4.3 Inspection procedures, instructions and/or check lists are provided and contain as a minimum the following:

5.10.4.3.1 Identification of quality characteristics to be inspected.

5.10.4.3.2 Identification of those individuals or organizations responsible for performing the inspection operation.

5.10.4.3.3 Acceptance or rejection criteria.

5.10.4.3.4 Description of the method of inspection.

5.10.4.3.5 Evidence of satisfactory completion and certification of inspection and materials.

5.10.4.3.6 Record of the results of the inspection.

5.10.4.3.7 A method of follow-up and conclusion to all final analyses.

5.10.4.4 The required quality shall be maintained even when inspection is not possible or disadvantageous. This is achieved through indirect control by monitoring of processing methods, equipment, and personnel. Both inspection and process monitoring is provided when control is inadequate without both.

5.10.4.5 Prior to performing an inspection operation, the following requirements are met:

5.10.4.5.1 Inspection procedures or instructions are available to include applicable drawings and specifications.

5.10.4.5.2 Inspection equipment is within the calibration standards.

5.10.4.5.3 Certifications of qualified personnel performing inspection are current.

5.10.4.5.4 All personnel required or requested to witness the activity have been notified and are present unless formal waivers have been made.

5.10.4.5.5 All safety precautions related to the health and well being of the participants and observers are evaluated prior to the start of the activity such as health, shielding, hard hats, and safety glasses.

APPENDIX C

NUCLEAR
QUALITY ASSURANCE
PROCEDURES

QAP Number: 2100
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INSPECTION

1.0 PURPOSE

The purpose of this procedure is to establish measures to control the inspections required during the design, procurement, construction, and operations of Nuclear Power Station, including preoperational testing, initial start-up, and inservice inspection. It also establishes the methods of control of inspection records and reports.

2.0 SCOPE

This QAP is applicable to all inspections of Q-List items and nuclear safety related activities performed by its agents, and suppliers/contractors.

3.0 RESPONSIBILITY

The Quality Assurance Manager is responsible for the development, control, and implementation of this QAP.

4.0 REFERENCES

4.1 ANSI N18.7, Administrative Controls for Nuclear Power Plants.

4.2 ANSI N45.2, QA Program Requirements for Nuclear Power Plants.

4.3 ANSI N45.2.4, Installation, Inspection and Testing Requirements for Instrumentation and Electric Equipment During the Construction of Nuclear Power Generating Stations.

4.4 ANSI N45.2.5, Supplementary QA Requirements for Installation, Inspection, and Testing of Structural Concrete and Structural Steel During the Construction Phase of Nuclear Power Plants.

4.5 ANSI N45.2.6, Qualifications of Inspection Examination, and Testing Personnel for the Construction Phase of Nuclear Power Plants.

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4.6 ANSI N45.2.8, Supplementary QA Requirements for Installation, Inspection, and Testing of Mechanical Equipment and Systems for the Construction Phase of Nuclear Power Plants.

4.7 ANSI N45.2.9, Requirements for Collection, Storage, and Maintenance of Quality Assurance Records for Nuclear Power Plants.

4.8 ASME Boiler and Pressure Vessel, Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components.

4.9 Nuclear Quality Assurance Manual.

4.10 OAP 1040, Training and Qualification of Non-QA Personnel.

4.11 QAP 2030, Design Control.

4.12 QAP 2040, Procurement Document Control.

4.13 QAP 2050, Instructions, Procedures and Drawings.

4.14 QAP 2140, Inspection Test and Operating Status.

4.15 QAP 2170, Quality Assurance Records.

4.16 QAP 2180, Audits.

5.0 FORMS

Not Applicable.

6.0 GENERAL

The Nuclear Quality Assurance Program requires a system of inspections during design, fabrication, assembly, construction, preoperational testing, start-up, and operations of Nuclear Power Station to verify the conformance of Q-List items and nuclear safety related activities to established quality requirements, and a record system to document the completion of inspection activities. Inspection activities are controlled in accordance with this QAP and the following related QAP's:

6.1 QAP 2101, Inspection Check Lists.

6.2 QAP 2102, Inspection Methods.

7.0 PROCEDURE

7.1 Inspection of Q-List items and nuclear safety related activities are conducted in accordance with approved written inspection procedures which define the inspection parameters to verify conformance with quality and design criteria. The following measures shall be provided for by inspection procedures:

7.1.1 Description of the inspection to be performed and identification of the equipment or activity inspected.

7.1.2 Required inspection check lists.

7.1.3 Required test and measuring equipment including calibration requirements.

7.1.4 Personnel training and qualification requirements.

7.1.5 Assurance that personnel performing the inspection are independent of the activity being inspected.

7.1.6 Assurance that all pertinent instructions, procedures, drawings, and related documents are available prior to the inspection.

7.1.7 Inspection methods or techniques.

7.1.8 Appropriate accept/reject criteria.

7.1.9 Requirements for the documentation and resolution of deficiencies and nonconformances.

7.1.10 Requirements for tagging, marking, or stamping to indicate current inspection status.

7.1.11 Requirements for documenting and disposition of inspection results.

7.1.12 Identification of mandatory hold and witness points, including resolution of deficiencies and nonconformances before continuation of the inspection or processing.

7.1.13 Inservice inspections are identified by inspection frequency and are to be performed during the station lifetime.

7.2 The Project Engineer is responsible to assure that inspection requirements for the design, procurement, and construction phase are identified and incorporated into appropriate design, procurement and construction documentation in accordance with QAP 2030, Design Control, QAP 2040, Procurement Document Control and QAP 2170, Quality Assurance Records. He is responsible to assure that agents and suppliers/contractors properly document inspection results in accordance with design and procurement requirements.

7.3 The Station Superintendent is responsible to assure that inspection requirements for preoperational testing, start-up and the operations phase, including inservice inspections, are implemented by written inspection procedures which are prepared, approved, and controlled in accordance with QAP 2050, Instructions, Procedures and Drawings. He is responsible to assure that inspection reports and records are properly prepared and dispositioned in accordance with QAP 2170, Quality Assurance Records.

7.4 The following is a suggested list of items to be considered in the planning of inspections and the documenting of results:

- 7.4.1 Personnel performing inspection activities are trained and qualified in accordance with QAP 1040, Training and Qualification of Non-QA Personnel.
- 7.4.2 Inspections are scheduled to assure completion and evaluation on a timely basis.
- 7.4.3 Documented inspection results must be available onsite and accompany each Q-List item or nuclear safety related activity prior to final acceptance of the item or system.
- 7.4.4 Inspection results are a part of the permanent record of the inspected structure, system or component.
- 7.4.5 Following an inspection, systems are returned to a normal configuration and tagged, marked or stamped to indicate status, in accordance with QAP 2140, Inspection, Test and Operating Status.

7.5 Distribution of inspection records and reports shall be made to appropriate persons and organizations and should include the following:

- 7.5.1 Description of the inspection.
- 7.5.2 Specific identification of the item or activity inspected.
- 7.5.3 Date of inspection.
- 7.5.4 Inspection results.
- 7.5.5 Acceptability of results and/or corrective action resulting from nonconformance.
- 7.5.6 Identification and signature of inspectors and data recorders, as appropriate.
- 7.5.7 Identification and signature of final approving authority of of inspection results.

7.6 The Quality Assurance Manager is responsible to assure compliance with this QAP through periodic audits conducted in accordance with QAP 2180, Audits.

E-N-D

NUCLEAR TECHNOLOGY

INDEX

COURSE 27 - METROLOGY

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

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NUCLEAR TECHNOLOGY SERIES
INDEX
for
COURSE 27, METROLOGY (EIGHT MODULES)

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